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THE SPATIAL DEPTH OF ATTENTION: INTERPRETATION OF 3D INFORMATION FROM LINE DRAWINGS

BY

DANIEL J. PILON ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

DEPARTMENT OF PSYCHOLOGY

Edmonton, Alberta
FALL 1994

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SEPTEMBER 2, 1994

À mes *"mutins"*,

Michael, Stéphanie, Marie-Pier, Patrick et, Alexandre,

Ne laisse jamais l'opinion d'autrui précéder tes désirs,
que ces désirs soient personnels ou professionels.
Tes buts ne seront atteints qu'à force de travail bien motivé.
À y croire, tu y arriveras.

Issues you will confront are yours alone.
As a grain of sand in your eye,
nobody will appreciate the irritation
quite as sensitively as you will.

Quoi que tu fasses, quoi que tu dises, et quoi que tu penses,
et quoi qu'on en fasse, dise, ou pense,
honnêteté et humilité feront de tes buts une réalité.

Souviens-toi en! Je t'aime.
DjP.

ABSTRACT

Many researchers in object-recognition have proposed that parts of an object are derived by analyzing the object's edges and vertices. The underlying assumption is that early object-recognition processes operate directly on edges and vertices to determine which edges and vertices belong to the same object. The purpose of the reported research was to explore the contribution of vertices during early object-recognition processes. Although Donnelly, Humphreys, and Riddoch (1991) found that vertices alone can be grouped in parallel to derive 2D perceptual representations, no similar evidence is available for 3D object representations. Thus, the reported research focused on the recovery of 3D object representations from vertices.

Enns and Rensink (1991a) suggested that edges and vertices subserve the parallel recovery of 3D-orientation. However, they reported that 3D orientation is not processed in parallel from vertices alone. These findings do not address whether vertices alone yield 3D object representations. As a first step in answering this question, factors expected to influence the detection of a 3D-orientation difference in Enns and Rensink's task were examined in the first four experiments. Unlike Enns and Rensink' findings, the results show that 3D orientation is not derived in parallel from line drawings of 3D objects, whether from complete or vertex-only contours. However, when complete-contour objects were aligned in a display, then search performance improved once participants had become familiar with the task.

In Experiments 5 through 7, participants searched for an inconsistent vertex in multiple vertex-only contours of 3D objects. Extending Donnelly et al.'s task to line drawings of multiple 3D objects, parallel processing of vertices was expected to yield perceptual representations instrumental to the detection of inconsistent vertices. However, the data do not support this hypothesis: Inconsistent vertices were not detected in parallel across multiple-object displays. The pattern of results across repeated sessions suggest that participants can however develop search strategies to improve search rates.

The present results suggest that vertices can be used to process shape structure but that shape structure, including 3D orientation, is not processed in parallel in multiple-object displays. The results are interpreted to mean that vertices belonging to a single object might be processed in parallel, but that search across objects is carried out serially. In addition, the underlying position adopted is that a continuum of processing best characterized search, both as a function of stimulus parameters (e.g., blocked presentation, object alignment, and contour completeness) and task parameters (e.g., repeated practice).

ACKNOWLEDGEMENTS

This research was supported in part by a Natural Sciences and Engineering Research Council grant to Dr. Alinda Friedman. I would like to express my sincere gratitude to those who have helped make this part of my life as enriching as it could be.

I am grateful to

members of my Supervisory Committee, Drs. Alinda Friedman, Peter Dixon, Marcia Spetch, for pushing my intellectual limits.

I extend heart-felt thanks to

Gail Crombie for anchoring goals I tended to lose;
Helen Maskery for encouraging self-belief;
Alan Frank for pointing out objective self-criticism;
Dawn McArthur for being a friend, at heart, knowing when to stay away,
when to call for a coffee break, and when to let me rant and rave;
Barb Senko for editing when I could no longer read;
and all those who, over the years, accepted my mood swings when I
forsook life's pleasures because of work or I jeopardized my work for a change of pace.

Most of all, I owe more than I could ever repay to

my parents, Claude Pilon & Claudette Smith-Pilon,
for always caring and believing;
my siblings and their consorts, Marc, Pierre, Nathalie, Diane, France, &
Stéphane, for challenging why I keep doing what I am doing;
my grand-mother, *feue* Fernande Demers-Smith,
for knowing that a well-rounded education bears its rewards in life;
and friends, like Jeanne Dufresne and Daniel Marleau,
who decided to stick with me through it all, knowing that my priorities had to be shifted for a while, but would eventually shift back to what they used to be.

MERCI À TOUS!

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The Spatial Depth of Attention:
Interpretation of 3D Information from Line Drawings

Most models of object recognition assume that real-world objects are perceived based on boundaries arising from differences in brightness, texture, surface orientation, or other perceptual features. Whether asserted or assumed, line segments (i.e., edges) and line junctions (i.e., vertices) are of particular relevance to the identification of object boundaries (e.g., Bergevin, 1989/1991; Hummel & Biederman, 1992; Duncan & Humphreys, 1989; Enns, 1992; Julesz, 1981; Lowe, 1987; Marr, 1982; Perkins, 1972). For the present thesis, *object descriptions* refer to the initial perceptual descriptions derived from the specification of object boundaries. It is assumed that object descriptions guide later processing of the visual input to generate functional mental representations (cf. Lowe, 1987; Marr, 1982). Yet, the true nature of the progression from edges and vertices to object descriptions needed for mental representations still eludes researchers.

In trying to understand this processing transition, some authors have claimed that different vertex types serve different functions in the generation of object descriptions (e.g., Enns, 1992; Horn, 1986; Hummel & Biederman, 1992; Marr & Hildreth, 1980). Yet, theoretical suggestions implicating vertices in object recognition (e.g., Attneave, 1974; Draper, 1978; Huffman, 1971; Leeuwenberg, 1971; Simon, 1967) remain mostly unsubstantiated in the empirical literature (but see Biederman & Ju, 1988; Donnelly, Humphreys, & Riddoch, 1991; Penrose & Penrose, 1958). The transition from two-dimensional (2D) image features to three-dimensional (3D) representations is the focus of the present thesis. The reported research was designed to document (1) the relative contribution of connected and unconnected vertices to the detection of a 3D-orientation difference and (2) the relative ease with which a misaligned vertex can be detected when it is embedded among contours that represent 2D, 3D, and quasi-3D objects.

Donnelly et al. (1991) recently reported evidence showing that unconnected vertices by themselves can yield sufficient information to derive 2D object descriptions. Furthermore, they found that the object description of a single 2D object can be derived in parallel from information available in vertices alone. That is, their subjects took the same amount of time to detect a single misaligned vertex in a square, pentagon or hexagon comprised of only unconnected vertices. Thus, the same amount of time is required to abstract an object description, independent of the number of vertices in an object, suggesting that vertices are processed simultaneously (i.e., in parallel). A consequence of parallel processing of vertices, and the basis of Donnelly et al.'s conclusions, is that the presence of a vertex inconsistent with the suggested object description is also detected from parallel processes. Donnelly et al. concluded that the colinearity of vertices within a single object underlies the parallel computation of object descriptions, the result of which is sufficient to detect an inconsistency in the suggested object description. The notion that colinearity of vertices subserves the processing of object contours will be discussed in greater detail when reviewing their research.

Enns and Rensink (1991a) examined the potential for line segments forming 3D contours to provide 3D-orientation information. In contradistinction to Donnelly et al., they found that vertices are not sufficient to recover 3D orientation in parallel from line drawings. These authors claimed that 3D orientation of line drawings requires the whole system of line relations to yield parallel search functions. Colinearity of vertices, though sufficient for the parallel recovery of an object's structure, is not sufficient for the parallel recovery of an object's 3D orientation.

The contrast between Donnelly et al.'s and Enns and Rensink's findings may result from differences in their methodologies, although both research teams used a visual-search task. Both studies will be reviewed shortly; however, gross differences are noted here. First, Donnelly et al. used stimuli depicting 2D contours; Enns and Rensink used stimuli depicting 3D contours. Second, Donnelly et al.'s displays depicted single objects, whereas Enns and Rensink's displays included up to 12 objects. Finally, in Donnelly et al.'s task, observers searched for an inconsistent vertex (i.e., they focused directly on the vertices). In contrast, observers in Enns and Rensink's study searched for a difference in 3D orientation (i.e., attention focused away from vertices per se).

The differences between the methodologies are potentially consequential for determining what information is available from vertices for the purposes of object recognition. For example, could Donnelly et al.'s finding of parallel grouping of vertices be restricted to 2D contours? If not, the parallel grouping of vertices belonging to a single object might have occurred with Enns and Rensink's 3D stimuli. However, their procedure was not designed to address this issue. What if grouping of vertices is limited to single-object displays? Although search for an inconsistent vertex occurs in parallel in single-object displays (Donnelly et al., 1991), search in multiple-object displays might not afford access to separate object descriptions. The present thesis attempts to document whether a first approximation of a shape's 3D structure, something akin to Marr's (1982) 2½-D sketch (i.e., an object description), is derived in parallel from the specification of boundaries based on vertices alone. To achieve this goal, two sets of experiments were conducted. In the first four experiments, performance in a visual-search task was compared when participants searched for a difference in 3D orientation among aligned or randomly-arranged line drawings of 3D blocks comprised of either only vertex or complete contours. The last three experiments assessed the contribution of vertex organization on the detection of a misaligned vertex with 2D, 3D, and quasi-3D vertex-only contours. Taken together, both sets of experiments were designed to bridge the findings of Enns and Rensink's (1991a) and Donnelly et al.'s (1991) studies.

In the first set of experiments to be reported here, factors expected to influence detection of a 3D-orientation difference in Enns and Rensink's (1991a) task were examined. More precisely, the influence of object alignment on search for a 3D-orientation difference was examined by comparing visual-search performance in multiple-object displays in which the objects were either aligned or randomly arranged. In addition, repeated practice on the task was considered, and eventually adopted, as a significant component of the experimental procedure. Contrary to Enns and Rensink's findings, the data from these experiments suggest that 3D orientation is not typically recovered in parallel. Some conditions, however, can lead to relatively flat search performance, statistically bordering on parallel search functions. These conditions include alignment of objects, blocked presentation of stimulus type, and repeated practice on the task. These data are discussed both in terms of Enns' (1992) model for the parallel recovery of 3D orientation from line drawings and in terms of Donnelly et al.'s (1991) notion of perceptual grouping.

In the second set of experiments, Donnelly et al.'s task was extended to multiple-object displays of 3D-object line drawings. Three experiments examined performance on search for a misaligned vertex with vertex-only contours of 2D and 3D objects. The results of these experiments were expected to extend Donnelly et al.'s finding that vertices belonging to a single object are processed in parallel in the context of multiple-object displays. The pattern of results shows that search across an array of objects, whether 2D or 3D, generally relies on serial scanning of the objects. As with search for 3D orientation in the first set of experiments, observers did not produce parallel search functions when searching for a misaligned vertex. This finding is a notable extension of Donnelly et al.'s findings. Interestingly, across the three experiments, some observers generated search functions that suggest parallel processing of the entire display. The data from the second set of experiments are discussed in the context of visual-attention postulates as they relate to the recovery of object descriptions needed for purposes of object recognition.

The following section reviews basic findings and theoretical notions associated with the visual-search task. A review of Enns and Rensink's work follows. A comparison of their work with Donnelly et al.'s research establishes the discrepancies between these two studies, identified earlier, in the context of the rationale for the present work.

Visual Search: Data and Theory

There is ample evidence that the visual system processes information in a series of stages. As an example, some researchers maintain that during the initial stage some visual discriminations are made effortlessly, in parallel across the visual field, and without attention. Neisser (1967) called this stage the *preattentive* stage and posited that it was during this stage that simple features are registered. The preattentively registered features are recombined into complex representations via later visual operations. Conjoining preattentive features requires focused attention and must be carried out serially (e.g., Broadbent, 1970; Duncan, 1980; LaBerge, 1973; Neisser, 1967; Posner, 1978; Treisman, 1988).

The recombination of primitive visual elements to form detailed mental representations is also an integral part of many object-recognition models (e.g., Hummel & Biederman, 1992; Lowe, 1987; Marr, 1982; Palmer, 1977). However, whether these primitive elements are processed preattentively for object-recognition remains unanswered. In particular, vertices have been earmarked as primitive elements by extant theories of object-recognition (e.g., Enns, 1992; Horn, 1986; Hummel & Biederman, 1992; Lowe, 1987; Marr & Hildreth, 1980) but have not been shown to be processed in parallel, much less preattentively, for the abstraction of 3D object descriptions.

Treisman, among other researchers (e.g., Banks & Prinzmetal, 1976; Kahneman, 1973; Neisser, 1964, 1967), investigated what features or properties are registered preattentively and how they are recombined to form a representation of the viewed world. Her initial solution (Treisman, 1982, 1985, 1988; Treisman & Gelade, 1980; Treisman, Sykes, & Gelade, 1977) was to propose that simple features of the 2D retinal image, such as color and line orientation, are registered rapidly and in parallel into separate spatial maps sensitive to distinct dimensions. Locations in a feature map correspond to retinal locations; the presence of a given feature in the visual stimulus activates the corresponding location in the feature map for that feature. The partitioned representations encoded in these separate feature maps are then integrated to form cogent visual representations. Kahneman and Treisman (1984) proposed that focused attention acts to join features into a temporary, or *episodic* (cf. Tulving, 1972), representation of the current view (also see Marr, 1976).

Treisman and her coworkers used a visual-search task, among other tasks, to confirm predictions arising from feature-integration theory (Treisman, 1982, 1985, 1988; Treisman & Gelade, 1980; Treisman & Gormican, 1988; Treisman & Paterson, 1984;

Treisman & Schmidt, 1982; Treisman & Souther, 1985; Treisman et al., 1977). In a visual-search task, observers must detect a target embedded in nontargets (e.g., a red target in a field of green nontargets). The primary diagnostic Treisman uses to assess preattentive processing is the occurrence of automatic target detection in search tasks. This phenomenon is known as *pop out*, because the target tends to pop out of the display, despite the number of objects in the display. One index used to infer parallel processing is relatively flat and nonlinear search functions (but see Townsend & Ashby, 1983) when response times are plotted as a function of the number of objects in a display (i.e., display size). When these functions are obtained, that is, when targets are detected rapidly and show little dependence on the number of objects in the display (Treisman & Gelade, 1980), the inference can be made that target-defining properties form part of the preattentive representation . As a rule, a 10 ms/item criterion has been adopted in the literature (e.g., Cave & Wolfe, 1990; Treisman & Gelade, 1980) as evidence of parallel processing, suggesting that no attentive operations are required for the detection of such targets. However, Enns (personal communication, August 24, 1994) points out that an absolute criterion is problematic because shallow slopes can be obtained for widely differing reasons. For example, search for easily discriminable targets can result in shallow slopes compared to less discriminable targets. Search can be made easy or difficult for any feature or conjunction by increasing the clarity or discriminability of the stimuli (also see Duncan & Humphreys, 1987; Townsend & Ashby, 1983). In the present thesis, the view that stimulus differences are relative is adopted. As a consequence, slopes will not be compared to a standard criterion; rather, relative differences in search performance between conditions will be discussed. Nevertheless, it should be noted that relatively flat search functions in the visual-search paradigm have been taken as evidence by Treisman and others e.g., (Klein & Farrell, 1989; Pashler, 1987; Treisman & Gelade, 1980; Wolfe et al., 1989) for parallel processing of the display.

Treisman repeatedly produced evidence of preattentive pop out for simple visual features. For example, Treisman and Gelade (1980) found that visual search for simple features (e.g., a pink target in a field of purple and brown nontargets) results in flat search functions. In contrast, when observers look for a target defined by a conjunction of features, search latencies increase linearly with display size. For example, observers produce positively sloped, linear search functions when searching for a red T in a field of red Xs and green Ts (Treisman & Gelade, 1980). Search functions such as these suggest that observers need to focus attention on each item, one at a time, to decide how properties, in this case color and letter, are conjoined.

Although flat search functions generally are observed with target-present trials, flat search functions are also observed with target-absent trials for some simple features. In addition, some visual stimuli (e.g., highly familiar stimuli like letters) that should theoretically be processed as conjunctions and yield linearly increasing search functions have been found to be processed, sometimes, as simple features, as suggested by flat search functions. Stimuli defined by the conjunction of features that yield search functions similar to stimuli defined by simple features (i.e., relatively flat search functions) will be discussed in the next section.

Treisman's feature-integration theory distinctly addresses the importance of attentive processes during the visual processing stream. As an example, evidence that attention is required to process feature conjunctions is available from the outcome of performance on search tasks requiring access to location information. When the target is distinguished by a simple feature, observers can identify the target, although sometimes incorrectly identifying its location. In contrast, the detection of conjunctive targets depends on correct localization. Treisman and Gormican (1988) reported that a location cue, presented briefly before onset of the stimulus, does not affect feature detection. The same location cue, however, drastically improves conjunction detection (but see Prinzmetal, Presti, & Posner, 1986). Thus, the detection of a conjunction requires that attention be focused at the location of the conjunction. This claim will be reconsidered when discussing Enns and Rensink's (1991a) research.

Conjunction searches are further distinguished from feature searches by the relation between target-present and target-absent trials. Target-absent slopes are usually twice as steep as target-present slopes. This 2:1 ratio suggests the use of a serial self-terminating search strategy (Sternberg, 1966). Self-terminating serial search occurs when every object in a display is searched until a target is detected or, in the absence of a target, until every object has been searched. For target-present trials, only half the display must be searched, on average, to detect the presence of the target. Thus, when target detection is dependent on serial search, a 2:1 slope ratio is expected. For the present research, and to avoid the pitfalls of interpreting relatively flat search functions (cf. Townsend, 1971; Townsend & Ashby, 1983), search functions will be taken as evidence of serial processing when this 2:1 ratio is observed between target-absent and target-present trials. When this ratio differs from 2:1, it will be taken as evidence that different processes than self-terminating processes self-terminating processes are involved. In contrast, and independent of absolute slope values, if slope ratios remain within a 2:1 range, then it can be concluded that a serial process is used in such cases, although some conditions might yield more efficient serial search than others search.

As an example of different processes being used, consider the following situations. Search with target-absent trials does not necessarily require an exhaustive search of the display. The slope pattern for target-absent trials will vary depending on the general strategy adopted to process these stimuli from trial to trial. For example, observers might assess the average time needed for the target to pop out in target-present trials. The time estimate might then be used to set up a response criterion. Thus, if the average time for pop out has elapsed, the participants would determine that the target is absent. This strategy would circumvent the need to search the display in target-absent trials, and would produce equivalent slopes for target-absent and target-present trials (i.e., 1:1 slope ratio). Another strategy might be for observers to switch to a serial-scan strategy when enough time has elapsed without pop out. This strategy might be adopted to confirm that the target has not been missed (cf. Egeth, Jonides, & Wall, 1972). With this strategy, a flat slope obtains for target-present trials (because the target pops out), whereas a linearly increasing slope results from the serial scan of target-absent trials (e.g., Egeth et al., 1972; Treisman, 1982, 1991). When a confirmation strategy is adopted, the slope ratio is relatively large because of nearly-flat slopes for target-present trials and substantial slopes for target-absent trials.

To summarize, in Treisman's original feature-integration theory (1982, 1985, 1988; Treisman & Gelade, 1980; Treisman & Gormican, 1988; Treisman & Souther, 1985), the visual system begins by encoding a certain number of simple properties in spatiotopic feature maps. These properties are coded automatically and in parallel, without focused attention. The feature maps allow the detection of targets with a unique sensory feature, simply from the presence of activity in the separate feature maps. The pattern of activity in a spatiotopic map differs as a function of the property activating the map. A uniquely distinct feature will generate a pattern of activity in a unique location and as such will be detected but not necessarily identified. In this sense, it is not the feature per se that is preattentive; rather, it is its selection. In contrast to preattentive selection, when features must be selected and conjoined to specify objects, focused attention is required. In particular, attention operates from a master-map of locations in which discontinuities between features are registered without specification of the property involved. That is, from focused attention on a particular location of the master-map, all features specific to this location are selected automatically and in parallel by way of links to the separate feature maps. Finally, the selected features are entered in an episodic object representation (Kahneman & Treisman, 1984) for comparison with stored object representations.

It was suggested earlier that various factors can affect search performance, making it difficult to attribute search functions to serial or parallel processes. One obvious factor is the discriminability of stimuli. Under such circumstances, visual search is subject to *floor effects*, so that beyond a certain level of discriminability, all search appear to be equally effortless, even though other measures of visual processing might show processing differences. Related to floor effects is the fact that search difficulty above the floor grades smoothly (Enns, 1992). This last point leads to the notion that processing speed might best be viewed as continuous (i.e., very slow to very rapid search functions) rather than as dichotomous (i.e., serial and parallel search functions). This is not to say that serial and parallel processes do not occur, but rather than they may not occur independently of one another. In this context, a 2:1 ratio, independent of slope size, would allow a comparison between stimulus conditions in terms of factors that make searcg more or less efficient. However, even though a 2:1 ratio may implicate the use of serial processes, a deviation from this ratio value would not necessarily imply the use of parallel processes.

Evidence for a continuum of processing is best demonstrated by Neisser's (1967) finding that initially difficult search can be made easier with sufficient practice. Findings such as these suggest that search functions which result from serial processing might be altered (e.g., 1:1 ratio) when parallel processes are also involved. The continuum of processing might reflect a different mix of serial and parallel processes as a function of many factors. For example, the relative contribution of parallel processes to the overall processing might increase with extended practice (cf. Schneider & Shiffrin, 1977), leading to a continuous reduction in slopes. Factors such as discriminability of stimuli and practice co-operate to make absolute measures of search slope inappropriate for interpretation.

While the use of absolute criteria might initially give the illusion of support for serial or parallel processing, these kinds of conclusions can no longer be made with much justification (see Townsend & Ashby, 1983). For example, a strict distinction between serial (nonoverlapping successive operations) and parallel (simultaneously initiated processing) processing precludes the stochastic processing of individual items in a display and the variability in processing times from trial to trial. Although Townsend (1971, 1990; Townsend & Ashby, 1983) warned against definitive interpretations of response-time data to distinguish between serial and parallel modes of operation (also see Atkinson, Holmgren, & Juola, 1969; Egeth, 1966; Ross & Anderson, 1981), the heuristic value of the dichotomy continues to foster its use to explain aspects of perceptual processing. Thus, the distinction will be preserved in the present work, keeping in mind that parallel and serial processes can mimic one another. Differences between stimulus conditions will, however, be discussed in terms of relative (or quantitative) differences in slope and absolute (or qualitative) differences in slope ratios. Quantitative differences have already been discussed in the context of a continuum of processing. Qualitative differences will be assessed via search ratios for target-present and target-absent trials search rates for stimulus conditions being compared. Thus, as suggested by Sternberg (1966), a self-terminating serial search pattern can be inferred from a 2:1 slope ratio between target-absent and target-present search functions. Functions not exhibiting this pattern will be attributed to qualitatively different processes.

Search for 3D Orientation in Line Drawings

Consistent with the view that a continuum between serial and parallel processing might best characterize processing in general, recent findings challenge the dichotomy between preattentive and serial processing advocated by feature-integration theory: It has been suggested that preattentive representations are much more complex than the aforementioned model suggests. For example, relatively flat search functions suggest that various combinations of simple features (or feature conjunctions) are processed in parallel (e.g., Brown, Weisstein, & May, 1992; Cohen, 1993; Donnelly et al., 1991; Egeth, Virzi, & Garbart, 1984; Epstein & Babler, 1990; Humphreys, Quinlan, & Riddoch, 1989; McLeod, Driver, & Crisp, 1988; Treisman & Sato, 1990; Wolfe, Cave, & Franzel, 1989). These findings are incongruent with the view that features are conjoined only via focused attention. Additional findings also suggest that the preattentive system is sensitive to aspects of 3D scenes available from 2D images (e.g., Downing & Pinker, 1985; Enns, 1992; Nakayama & Silverman, 1986a, 1986b; Ramachandran, 1988). For example, Ramachandran (1988) showed good parallel discrimination based on differences in shape from shading. The present research is based in part on Enns and Rensink's (1991a) task that suggests that some combinations of line segments are processed in parallel to derive information about the orientation of 3D objects. Such unexpected findings, peculiar because 3D information is usually construed as requiring a synthesis of 2D information, led Treisman to modify the feature-integration theory (Treisman, 1991, 1993; Treisman & Sato, 1990). Some modifications will be discussed after a review of Enns and Rensink's (1991a) work.

Enns and Rensink's stimuli consisted of line drawings depicting objects that differed in orientation. Observers were presented displays containing 1, 6, or 12 objects. For half of the displays, one of the objects (i.e., the target) in the display differed from all other objects (i.e., nontargets) by a difference in orientation. In a first experiment, when the target was defined by a difference in 3D orientation (see Figure 1, left panel), search functions were relatively flat. Readers are cautioned about interpreting the graph in Figure 1: Although the search functions in the left panel of Figure 1 appear parallel, the reported slopes for target-present and target-absent trials were 7 and 12 ms/item, respectively, yielding a slope ratio close to 2:1. This ratio is more consistent with serial than with parallel search. In comparison, search functions for topologically equivalent displays of 2D items (see Figure 1, right panel) were steep and also resulted in 2:1 ratio. Enns repeated this experiment (Enns, 1988; Enns & Rensink, 1990b, 1991a, 1992) and reported different search rates across studies, from 7 to 16 ms/item for target-present trials and from 12 to 21 ms/item for target-absent trials. Strictly speaking, and consistent with the notion of a continuum of processing, there is no sharp boundary between fast and slow search rates.

In the experiment of interest to the present work, Enns and Rensink (1991a, Experiment 6) tested whether edges and vertices are necessary and/or sufficient for the parallel recovery of 3D orientation from line drawings. Visual-search performance for orientation differences was measured for stimuli consisting only of vertices and for stimuli consisting only of straight edges (see Figure 2). When viewed individually, these objects still resembled 3D oriented blocks. The results of these two experimental conditions were compared to the nearly-flat search functions observed in Enns and Rensink's first experiment with complete-contour objects.

In the first condition (see Figure 2, left panel), performance was measured for displays consisting of 3D blocks lacking vertices. Search times were very slow and increased with the number of objects in the display. In the second condition (see Figure 2, right panel), search times across objects depicted with unconnected vertices were even slower than with displays of vertex-missing objects. There was a 2:1 ratio of slopes in both cases, suggesting serial search. These data, together with those from Figure 1, left panel, indicate that vertices are necessary, but not sufficient, for parallel processing of 3D orientation from line drawings in multiple-object displays. It is as though related unconnected vertices are treated as conjunctions, requiring directed attention, and connected vertices, in the form of complete contours, are processed as single entities.

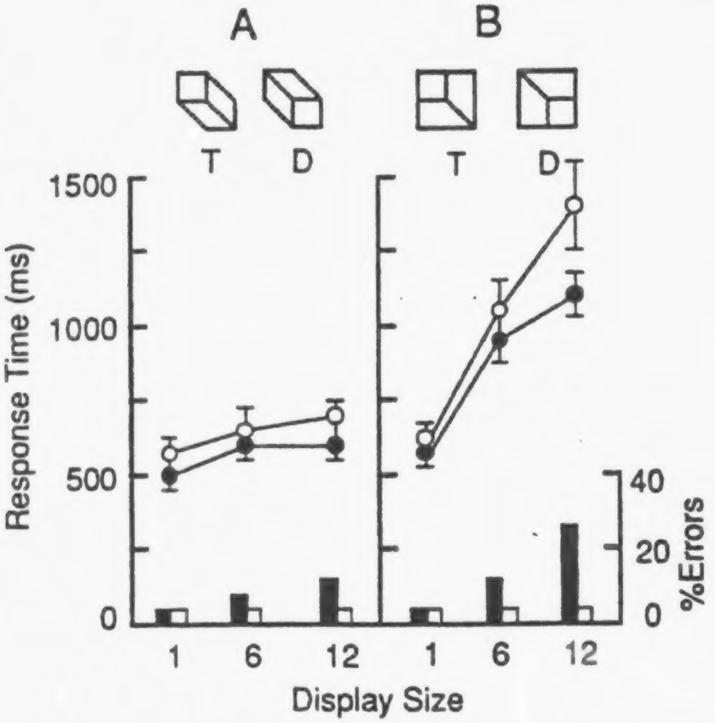


Figure 2. The target items (T), distractor items (D), and results in Experiment 1. (Closed circles and bars represent target-present trials; open circles and bars represent target-absent trials. Response time values are *M*± *SEM*.)

Figure 1. . Stimuli and data from Enns and Rensink (Experiment 1). See original figure caption (labeled 2 above) for figure legend. *Note*. From "Preattentive recovery of three-dimensional orientation from line drawings" by J.T. Enns and R.A. Rensink, 1991, *Psychological Review*, *98*, p. 338. Copyright 1991 by the American Psychological Association. Reprinted by permission.

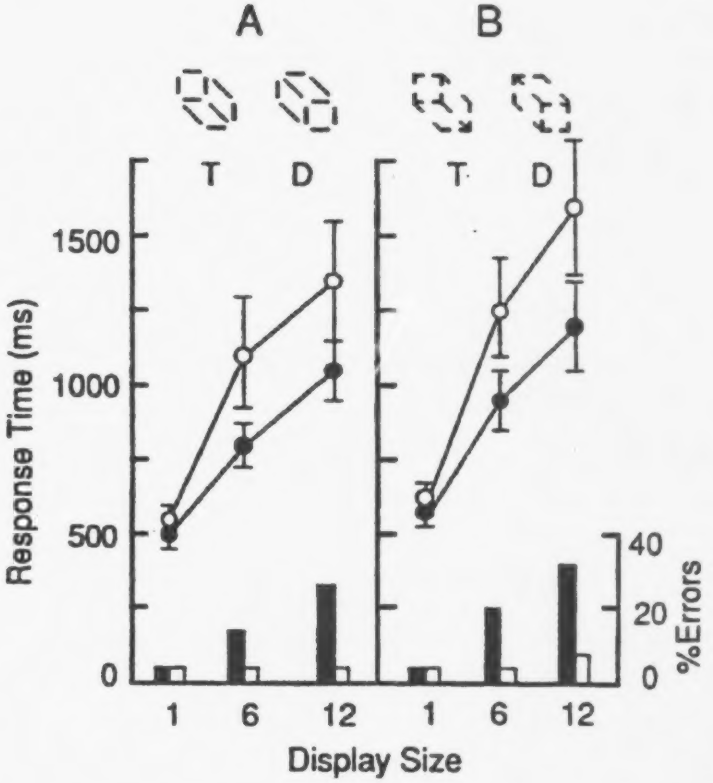


Figure 7. The target items (T), distractor items (D), and results in Experiment 6. (Closed circles and bars represent target-present trials; open circles and bars represent target-absent trials. Response time values are *M*± *SEM*.)

***Figure 2*.** . Stimuli and data from Enns and Rensink (Experiment 6). See original figure caption (labeled 7 above) for figure legend. *Note*. From "Preattentive recovery of three-dimensional orientation from line drawings" by J.T. Enns and R.A. Rensink, 1991, *Psychological Review*, *98*, p. 341. Copyright 1991 by the American Psychological Association. Reprinted by permission.

As mentioned earlier, Treisman's (1993) modified feature-integration theory addresses Enns and Rensink's findings. Although the basic tenets of preattentive and serial processing remain integral to the theory, new ways of processing conjunctions have been proposed to account for the preattentive accessibility to some conjunctions. For example, Treisman and Paterson (1984) revived Garner's (1974; also see Pomerantz, Sager, & Stoever, 1977) notion of integral stimuli and suggested that simple features can combine to produce emergent features. A feature is emergent if its presence is dependent on the combination of other features. For example, symmetry is defined by the combination of two elements that are mirror-images of one another. Attention to one physical element in the stimulus is not sufficient to predict processing differences based on the entire stimulus. The emergent feature (e.g., the symmetry) often predominates the processing of the stimulus. Emergent features differ from conjunctions in the sense that emergent features are conjunctions that are processed as a whole, whereas conjunctions require that each element be processed separately. Processing is wholistic in the sense that attention need not be allocated to individual elements in the display to detect the presence of an emergent feature. Treisman and Paterson (1984) contended that emergent features may themselves qualify as elementary building blocks of perception. If this is the case, then emergent features should behave like preattentive features. Treisman and Paterson pointed out the circularity of this argument and sought confirming evidence from other tasks.

In one task, observers were directed to detect a target (a circle with a gap in its contour) within an array of nontargets (complete circles) in a visual-search task (Treisman and Souther, 1985, Experiment 4). Evidence for the emergence of contour closure was also obtained when a target was defined as a triangle and nontargets were formed by rearranging the same three lines comprising the triangle (Treisman & Paterson, 1984, Experiment 1). In both situations, the ensuing search functions were not contingent upon display size, from which Treisman and Paterson concluded that closure was an emergent feature. In a second task, circles could apparently supply the additional feature (presumably closure) required to form illusory triangles from their component lines (Treisman & Paterson, 1984, Experiment 5). It is critical to note that these authors identified closure as the explicit presence of an uninterrupted outline. In line with evidence of emergent features, Treisman (1991, 1993; Treisman & Paterson, 1984; Treisman & Sato, 1990) incorporated in the theory the suggestion that the perceptual system registers properties characterizing objects in the real world, not simply 2D properties described at the retinal level. Such a modification could potentially support the preattentive encoding of 3D orientation with complete contours.

Preattentive Recovery of Object Descriptions

Although the modified feature-integration theory (Treisman, 1991, 1993) accommodates Enns and Rensink's (1991a) findings for 3D-orientation search with complete and incomplete contours, Donnelly et al.'s (1991) observations with vertex-only contours render Treisman's account less promising. Donnelly et al. reported that the conjunction of unconnected L-vertices can be effortlessly perceived as forming the contour of a geometric shape. In this sense, closure of contour as an emergent feature is not restricted to uninterrupted outlines as suggested by Treisman and Paterson (1984), but may also include contours formed by virtual lines connecting physically unconnected vertices.

Donnelly et al. used a variation of the visual-search task to demonstrate that an object description can be derived in parallel from vertices alone. Their hypothesis was that vertices forming a geometric contour (i.e., a square, a pentagon, or a hexagon) could be grouped in parallel and processed as a whole (i.e., an emergent geometric form). Consequently, they predicted that a vertex not belonging to the contour would be detected preattentively. As a related prediction, vertices forming a consistent contour were expected to be rejected preattentively as nontargets because of the consistent object description suggested by the parallel grouping of the vertices. For this effect to obtain, a condition was needed to control for the possibility that vertices can group in parallel, regardless of an emergent geometric form (see Duncan & Humphreys, 1989; Humphreys et al., 1989). Their first and second experiments compared performance with such stimuli (see Figures 3 & 4).

Donnelly et al.'s stimuli consisted of single, geometric shapes made up of vertices only. Display size was defined as the number of vertices in a display (four, five, or six vertices). For half of the stimuli, one vertex was rotated 180° at its apex (see Figure 3). The task consisted of deciding whether all vertices pointed in the same direction (outward) or whether one of the vertices pointed in the opposite direction (inward). A constant amount of time was required to detect an inconsistent vertex, independent of the number of vertices in the display. In addition, search slopes were equivalent (i.e., 1:1 ratio) for target-absent and target-present trials, even though target-absent trials required more time to process than target-present trials. This search pattern, however, did not hold (see Figure 4) when the vertices presumably could not be interpreted as forming the boundary of a polygon (i.e., all vertices, except the target, pointed inward; the target pointed outward). Search slopes for these stimuli suggest that observers were using a self-terminating serial search. Consistent with visual-attention accounts (e.g., Egeth et al., 1972; Townsend, 1990) is the fact that target-absent trials required more time to process than target-present trials.

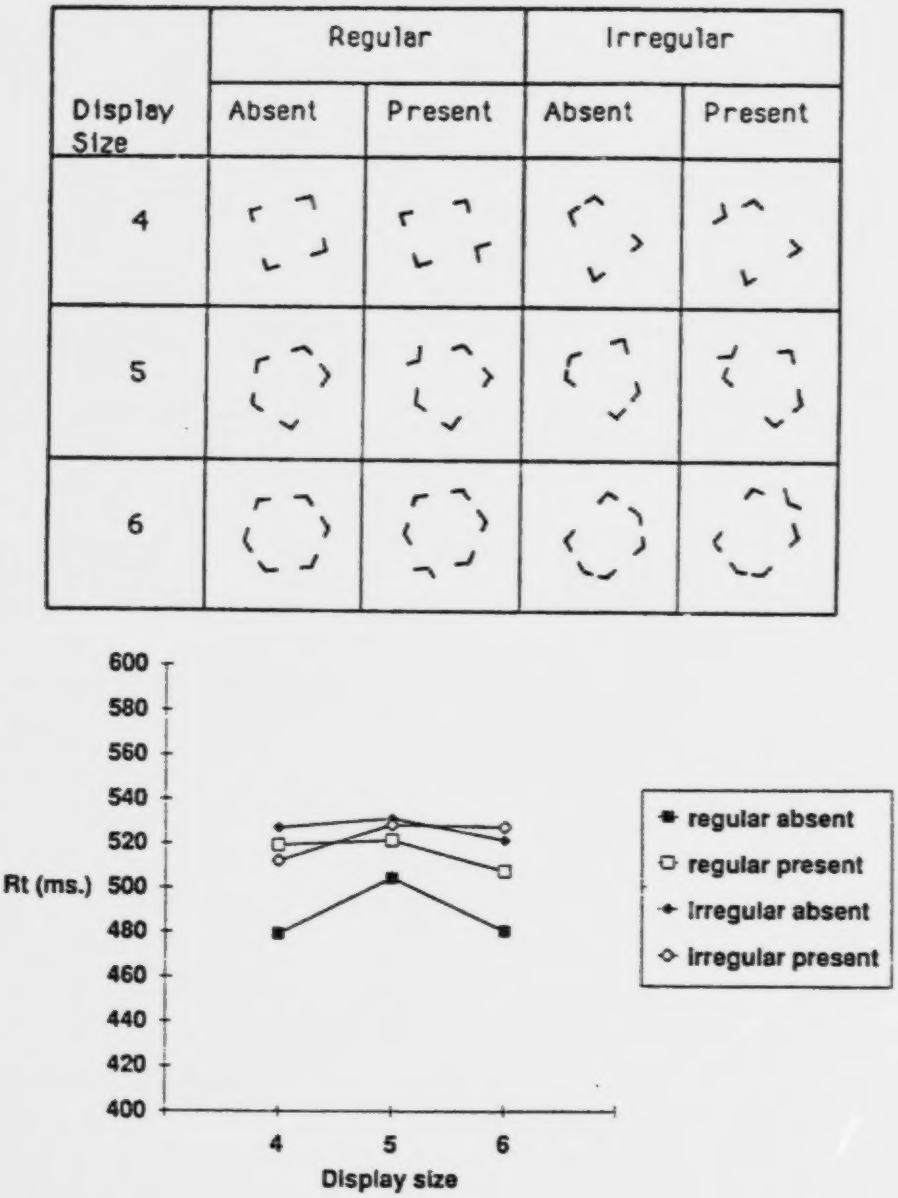
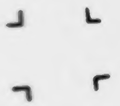
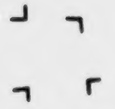
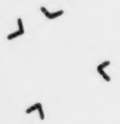
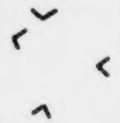
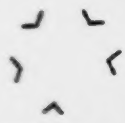
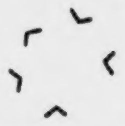
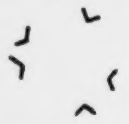
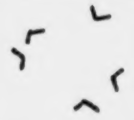
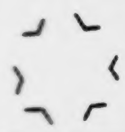
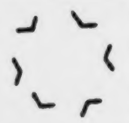
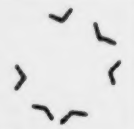
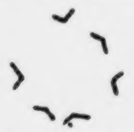


Figure 3. . Stimuli that form geometric contours and data from Donnelly et al. (Experiment 1). *Note*. From "Parallel computation of primitive shape description" by N. Donnelly, G.W. Humphreys, and J.N. Riddoch, 1991, *Journal of Experimental Psychology: Human Perception and Performance*, *17*, p. 563. Copyright 1991 by the American Psychological Association. Reprinted by permission.

Display Size	Regular		Irregular	
	Absent	Present	Absent	Present
4				
5				
6				

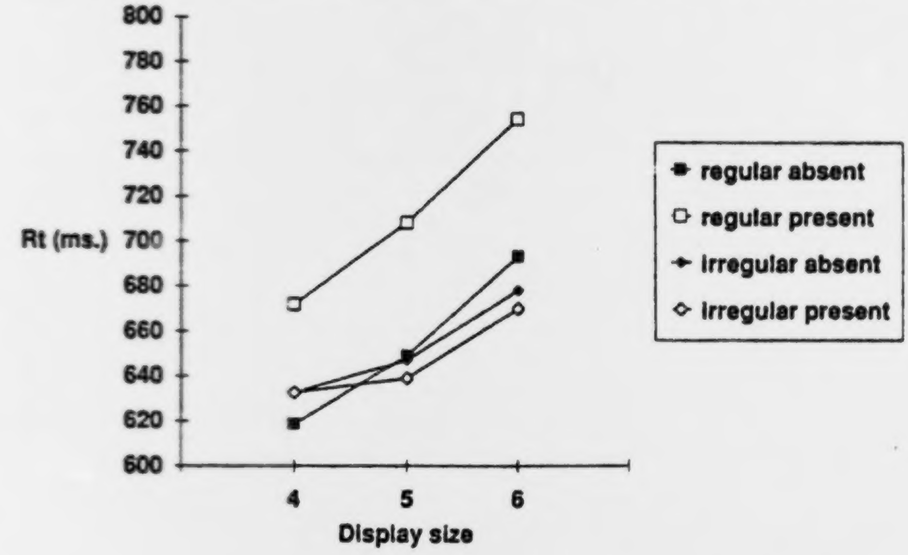


Figure 4. . Stimuli that form geometric contours and data from Donnelly et al. (Experiment 2). *Note.* From "Parallel computation of primitive shape description" by N. Donnelly, G.W. Humphreys, and J.N. Riddoch, 1991, *Journal of Experimental Psychology: Human Perception and Performance*, *17*, p. 565-566. Copyright 1991 by the American Psychological Association. Reprinted by permission.

The pattern of results across the two conditions implies that vertices in the first type of display were grouped and processed in parallel. Critical to claims of preattentive processing, slopes for target-present trials in the first experiment were flat or negatively accelerated (see Figure 3). Claims that vertex grouping occurred preattentively are also supported by relatively flat search functions observed with target-absent trials. In addition, slopes for trials with vertices plotted at regular intervals tended to be negative compared to slopes of trials with vertices plotted irregularly. Donnelly et al. concluded, following Humphreys et al. (1989), that search is relatively unaffected by the number of vertices present, provided the vertices configure into a single perceptual object. These authors suggested that grouping of vertices is based on gestalt properties such as colinearity of line segments and regularity.

Parenthetically, Donnelly et al. (1991, Experiment 4) also compared search performance for displays containing one or two vertex-only contours. The goal of this experiment was to determine whether the visual system can distribute attention across more than one object and still process vertices belonging to a single object in parallel across more than one object. Briefly, response times were longer for two-object displays, but slopes were relatively flat for both one- and two-object displays (13 and -11 ms/item for double and single configurations, respectively). Overall, the main effect of number of objects in the display suggests that observers have parallel access to object descriptions from different areas of the visual field. Donnelly et al., however, concluded that attention is limited to one object at a time because of the difference in response times. This experiment and their conclusions will be presented again when discussing the results of Experiments 6 and 7.

Donnelly et al.'s conclusions concerning colinearity of vertices are consistent with the general notion that alignment of elements in a display can facilitate perceptual processing (Bergen & Julesz, 1983; Julesz, 1985; Sagi & Julesz, 1985). The typical explanation for the effect of alignment on perceptual discriminations maintains that alignment generates a periodical texture in the display. In some sense, alignment generates an emergent feature characterizing the entire display. Thus, independent of the fact that displays consist of objects, the display itself can be viewed as a single object. As such, the emergent feature generated by the alignment of elements could foster parallel processing of the display. Any element in the display interrupting the texture gives rise to a discontinuity in the texture and, as such, is easily detected. Alignment of objects would therefore allow parallel processing of objects in a display that otherwise would be searched serially. Of interest here, is the fact that Enns and Rensink's (1991a) procedure to reduce alignment of objects (i.e., a 0.5° jitter of each object in the display) might not have been sufficient to disrupt the perception of alignment. This idea will be raised again when discussing the results of Experiments 1 through 4.

In the present thesis, it is proposed that the alignment of objects (and colinearity of their vertices) might facilitate search for an inconsistent object within a display. More precisely, when line drawings of 3D cubes are aligned with each other, and one object is inconsistent with the alignment (due to its orientation), then the misaligned object is expected to be detected relatively easily. Based solely on expected effects of alignment on search, search patterns with complete and vertex-only contours are not predicted to differ. The comparison of vertex-only and complete-contour displays as a function of display alignment is the primary concern of the first four experiments reported in this thesis.

Rationale

Recall that Enns and Rensink (1991a) reported that vertices are not sufficient to provide surface information necessary to derive 3D orientation in parallel from multiple-object displays. In contrast, Donnelly et al. (1991) claimed that vertices are sufficient to yield preattentive object descriptions of single 2D shapes, when the task is to detect a misaligned vertex. How can these two sets of findings be reconciled and incorporated in models of object recognition? One possibility is to bridge them by predicting search performance for stimuli that lie between the stimuli used by these researchers. Thus, the interpretation of the data for single-object displays of 2D contours (Donnelly et al., 1991) and multiple-object displays of 3D contours (Enns & Rensink, 1991a) can be linked by discussing either the processing of displays with multiple 2D contours (a condition similar to Experiments 6 and 7 of the present thesis) or single-object displays of 3D contours (as stimulus conditions in Experiment 7 of the present thesis).

As already mentioned, Donnelly et al. (1991) provided evidence that attention is limited to a single object at a time. This is the case when 2D surfaces are physically separated. What about 2D surfaces that are part of a 3D object? Donnelly et al.'s conclusion can be interpreted in one of two ways: The first possibility is that parallel access is limited to object descriptions of 2D contours, irrespective of whether they form part of a 3D object. The second is that 3D contours, like 2D contours, are processed as single entities. If the former is true, then 2D descriptions need to be synthesized into 3D descriptions (cf. Epstein & Babler, 1990). If the latter is true, then information about the surfaces of a 3D object is expected to be available in parallel.

Regardless of the way in which a single 3D object is processed, Donnelly et al.'s claim that attention is limited to a single object is consistent with Enns and Rensink's conclusion that 3D orientation is not recovered from the parallel processing of vertices alone. There is, however, an inconsistency between the conclusion of both studies. Enns and Rensink's findings suggest that attentional resources required to recover object descriptions from incomplete contours are not required to recover 3D orientation with complete contours, yet Donnelly et al. found that vertices alone can be used to recover a 2D object description in parallel. Incomplete contours in multiple-object displays might require that an object description be abstracted for each object before 3D orientation can be processed. Thus, the 3D object description, but not its 3D orientation, might be derived in parallel from vertices alone. Search for 3D orientation with incomplete contours would here again result in linearly increasing search functions, but search that could be based entirely on 3D object descriptions would yield relatively flat search functions.

To reiterate, the present thesis uses two sets of experiments to integrate findings reported by Enns and Rensink (1991a) and Donnelly et al. (1991). The underlying goal was to assess differential processing of information available from line drawings of 3D objects comprised of vertices only. This goal is achieved with two sets of experiments. In Experiments 1 through 4, Donnelly et al.'s conclusion that colinearity of vertices underlies the parallel grouping of vertices into 2D object descriptions is extended to the hypothesis that colinearity of objects (i.e., object alignment) might allow the parallel detection of 3D orientation from vertex-only 3D stimuli. Thus, in Experiment 1, search performance for 3D orientation differences is compared for displays consisting of either complete or vertex-only contours as a function of whether they are aligned or randomly arranged. Although objects in Enns and Rensink's displays were randomly jittered, a direct comparison of aligned and randomly-arranged displays is expected to yield evidence of processing differences.

With complete-contour objects, aligned displays are expected to yield relatively flat search functions compared to randomly-arranged displays. This prediction is based on the assumption that alignment of objects generates an emergent feature of the display that can be used to process the display in parallel. Even though Enns and Rensink concluded that 3D orientation with complete contours can be processed in parallel, the slope ratio they obtained suggests that the observers probably carried out a very fast serial search. Note that if 3D-orientation detection with complete contours in the present research does not yield relatively flat search functions with randomly-arranged displays, then Enns and Rensink's search functions might reflect a relatively weak disturbance of object alignment that still enables the use of alignment to process the displays. To test the hypothesis that alignment of objects in a display might facilitate the detection of a 3D-orientation difference, the displacement of objects (i.e., object jitter) in randomly-arranged displays of the present research will be larger than the displacement used by Enns and Rensink (see General Methods). Consequently, slopes for randomly-arranged displays are expected to be steeper than slopes for aligned displays. A comparison of slope ratios between aligned and randomly-arranged conditions will suggest whether different processes are operating (as suggested by differences in slope ratios) or whether the displays are processed in essentially the same manner, but show relative differences in speed of processing (indicated by similar ratios but different absolute slopes).

With vertex-only contours, the same comparison involving object alignment will indicate whether virtual contours are sufficient to yield an emergent feature of the display. That is, it may be that parallel processing of the display can occur with vertex-only contours as it does with complete contours. If so, then relatively flat search functions, together with a slope ratio different from a 2:1 ratio, might suggest that closure of contour can also be recovered in parallel with aligned, vertex-only displays. If the assumption that alignment of objects generates an emergent feature of the display does not hold with vertex-only contours, then a 2:1 slope ratio is expected with aligned and randomly-arranged displays. Thus, relative differences in slope between conditions, together with a 2:1 slope ratio would support the notion of a continuum of processing. As an example, seen with search functions reported by Enns and Rensink (see Figures 1 and 2), a 2:1 ratio obtains, even though there is an obvious difference in search rates between complete and vertex-only contours.

Because the hypotheses of Experiment 1 were unsupported in a within-subject design, Experiments 2 and 3 were designed to delineate the conditions leading to parallel detection with complete contours. In Experiment 2, randomly-arranged displays of complete contours are examined in an attempt to replicate Enns and Rensink's finding with similar stimuli. In Experiment 3, search functions for aligned and randomly-arranged displays of complete contours are compared. The effect of practice on the task is also examined, with participants completing the task over four sessions. As a result of partial replication of Enns and Rensink's findings with complete contours in Experiment 3, conditions resulting in relatively fast search with complete contours are used in Experiment 4 to examine search patterns for 3D orientation with vertex-only contours.

In the second set of experiments (Experiments 5 through 7), Donnelly et al.'s task is extended to multiple-object displays of vertex-only contours. That is, observers were asked to search an array of vertex-only contours for a misaligned vertex in one of the contours. The goal of these experiments is to compare performance for search when the target is a misaligned vertex embedded in vertex-only contours depicting 2D, 3D, and quasi-3D objects. If Donnelly et al.'s findings extend to line drawings of multi-object displays, then a misaligned vertex should be detected in parallel with 2D contours. Furthermore, if their conclusions generalize to 3D contours, similar parallel search functions are expected with 3D contours. The task is carried out separately for 3D and 2D contours (Experiments 5 and 6, respectively) as well as in a between-subjects design with quasi-3D objects (Experiment 7).

GENERAL METHOD

The following description of the experimental paradigm applies to every experiment, unless otherwise indicated. Information needed for an overall perspective of the methodology is provided here and details pertaining to specific experiments are stated therein. For the most part, details of the experimental design and stimuli were obtained from various sources published or presented by Enns and his colleagues (Enns, 1988, 1990, 1992; Enns, Ochs, & Rensink, 1990; Enns & Rensink, 1990a, 1990b, 1991a, 1991b, 1992; Rensink, 1990).

Design and Stimuli

The stimuli were created using a combination of two drafting software packages (AutoCAD Release 11.0, 1991; Generic CADD 6.0, 1992). Displays were saved in HPGL-format drawing files (Hewlett-Packard, 1989) and displayed using Turbo C/Turbo C++ (Borland, 1988/1991) graphics library functions. Stimulus displays contained 2, 6, or 12 items and were black line drawings presented on a white background (luminance of 0.08 and 13.8 cd/m^2, respectively). Target and nontarget items (see Figure 5) were created from line segments that differed only in their spatial arrangement. Each item in a stimulus display corresponded to a line drawing intended to depict a 3D elongated block.

In generating the stimuli, items were centered in the cells of a 4 X 6 notional grid subtending 10° X 15° of visual angle (the lit area of the screen was 13° X 19°). Each item subtended less than 1.5° (approximately 1.36°) of visual angle in any direction. In contrast to Enns and Rensink's displays, with a 2-pixel line width (personal communication, August 24, 1994), the line width for all items was one pixel. All displays were centered on the screen. These stimulus constraints are identical to those used by Enns and Rensink (1990a, 1991a).

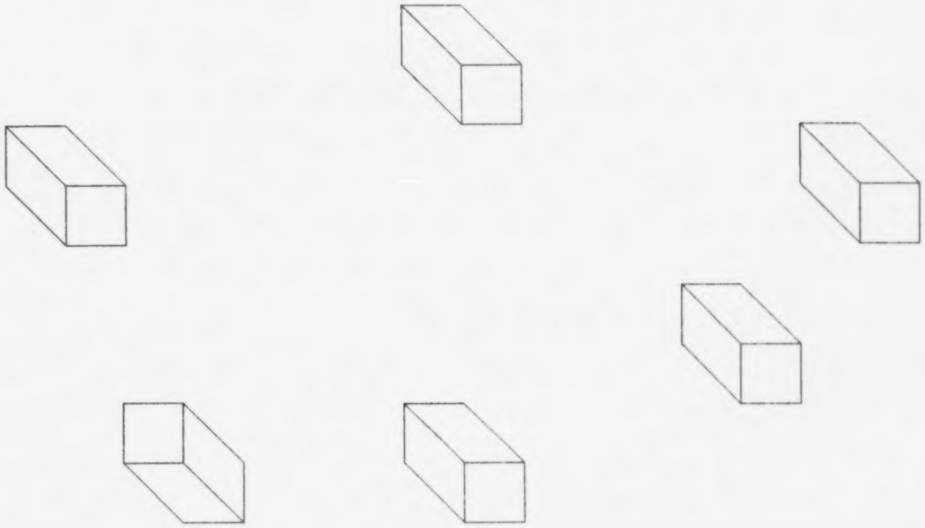


Figure 5. Example of a complete-contour, randomly-arranged, target-present stimulus.

The way in which the target differed from other items in a display will be identified separately for each experiment. The target was present in a display for half of the trials. Whenever present, the target appeared equally often at each location of a given display size. Conditions were presented randomly throughout the trial sequence. The trial sequence was constrained by the following criteria: (1) the same display was never presented on consecutive trials, (2) whenever present, the target was never presented at the same location on consecutive trials, and (3) the same response was required on no more than four consecutive trials.

Stimulus factors

Different combinations of stimulus factors were used in each experiment. Although these specific combinations will be stated in their respective experimental sections, each stimulus factor is defined here.

Completeness of contours. For some experimental conditions, the stimuli consisted of 3D blocks depicted with complete contours (see Figure 5); for other conditions, stimulus contours were fragmented and made up only of edges forming vertices (see Figure 6). Vertex-only contours were generated by deleting 50% of the contour at midsegment. In other words, half the length of each segment of an item was deleted from the midpoint, leaving 25% of the length at each end of the segment. Thus, each item consisted only of vertices defining the item. These stimuli are similar to those used by Enns and Rensink (1991a, Experiment 6).

Alignment of items. Items in a stimulus display could be presented in one of two ways (compare Figures 5 and 6). Some stimuli consisted of displays with items centered within cells of the notional grid. This condition is referred to as the *aligned* condition (see Figure 6). The remaining stimuli were *randomly-arranged* in the display (see Figure 5). That is, each item in the display was randomly displaced about its central location in the notional grid to prevent search from being based on item alignment. Each item in a display was displaced along one of eight radii from the centre of the grid cell. To increase the apparent randomness of the objects in the display, items were maximally displaced (approximately 2.5° of visual angle), compared to Enns and Rensink's displacement of 0.5° of visual angle. As will be seen in the results of Experiments 1 and 2, the increase in displacement compared to Enns and Rensink's displacement is important to search performance.

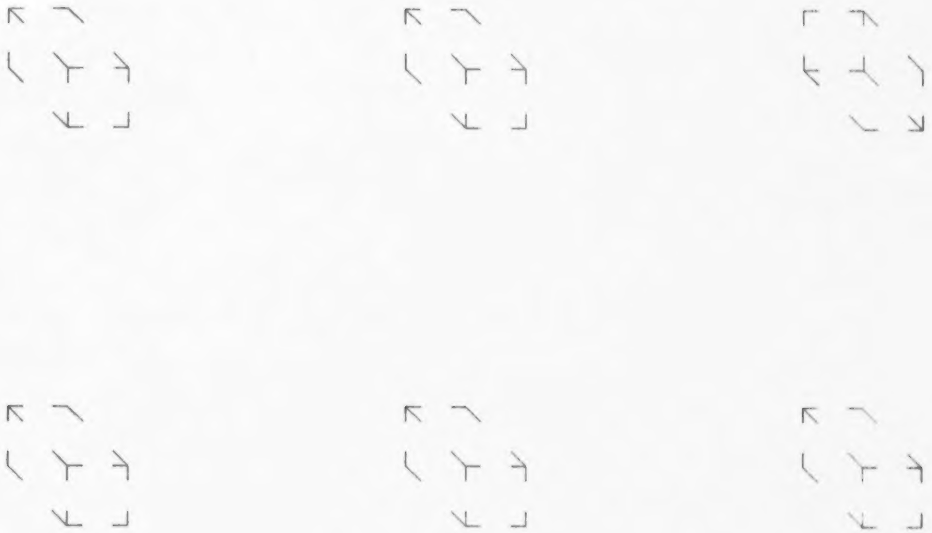


Figure 6. Example of a vertex-only, aligned, target-present stimulus.

Target type. Each item of a display coincided with the 2D orthographic projection of the 3D block from one of two viewing directions: either from above or from below. The target was always viewed from above because Enns and Rensink (1991a, Experiment 7, Condition E) found a search asymmetry between targets viewed from above and targets viewed from below. The latter are detected more readily than are the former, consistent with Ramachandran's (1988) claim that the visual system prefers to segregate textures based on the assumption that scenes are lit from above. Depending on the task, one of two target types was used in the experiments. The first target type was based on Enns' (1992) procedure and the other on Donnelly et al.'s (1991). The first consisted of a 3D block viewed from below (see Figures 5 and 6) in a field of nontargets viewed from above. The task using this stimulus configuration consisted of detecting the difference in orientation between the target and the other items in the display.

Displays associated with the second type of target consisted exclusively of vertex-only contours (see Figure 7). The target in this situation was defined as the item with a misaligned outer vertex (i.e., a concave vertex) in relation to the remaining vertices comprising the contour. All other items in a display were made up of convex vertices. The task with this type of stimulus consisted of detecting the presence of an item with an inconsistent vertex in the display. This manipulation is similar to the one used by Donnelly et al. (1991). This particular target type will be re-introduced when it is first used in Experiment 5.

Apparatus

The stimuli were displayed on a NEC MultiSync 3D video screen controlled by a PC equipped with an ATI VGA 1024 video board. Participants responded to each trial by touching one of two touch-plates connected to the computer. Stimulus presentation, timing, response collection, scoring, and feedback were controlled by the computer.

Procedure

At the start of an experimental session, participants were read instructions specific to the task to be completed (see Appendix A for instructions). Participants were asked to respond as quickly and as accurately as possible. They were directed to touch the right touch-plate, with their right index finger, for target-present displays, and the left touch-plate, with their left index finger, for target-absent displays. In each experimental session, participants completed 24 practice trials, followed by 576 experimental trials. The experimental trials were broken down into two sets of 288 trials to provide a short pause for participants. The number of trials per condition was dependent on the specific experiment

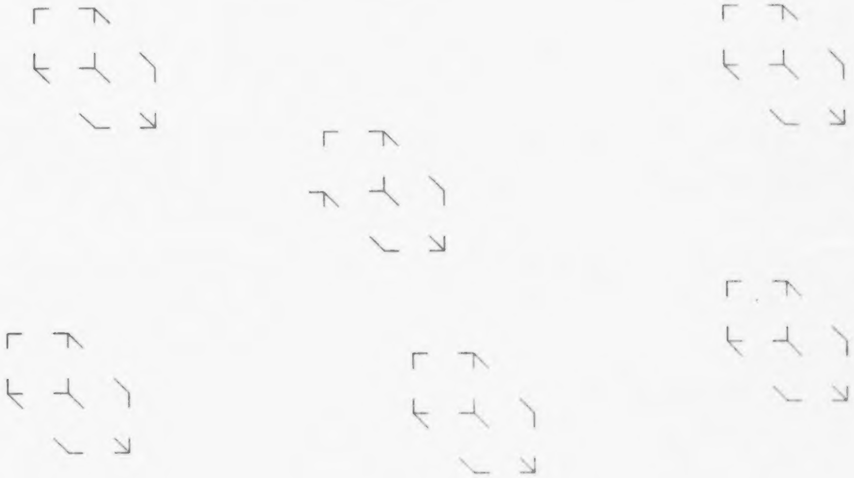


Figure 7. Example of a target-present, vertex-only stimulus used in Experiment 5.

and will be reported as each experiment is discussed in detail. For some experiments, participants completed only a single session; for others, participants were asked to complete four experimental sessions within 4 days.

The stimuli were presented in a dimly lit room. Participants were dark-adapted during the initial instructions. Each trial began with a fixation symbol in the center of the screen, lit for 500 ms, followed by the stimulus display. The display remained visible until a response was given. Once a response was given, an auditory feedback signal was sounded (a single 100-ms 600-Hz tone or two 50-ms 440-Hz tones separated by 25 ms for correct or incorrect responses, respectively) and the display was replaced by a feedback symbol (*plus* for correct and *minus* for incorrect). The feedback signal served as the fixation symbol for the following trial.

Subjects

Graduate students, senior undergraduates, and research assistants from several University of Alberta departments were solicited for participation. Only right-handed individuals were recruited. Participants were also required to have normal or corrected-to-normal vision. Participants received $7.50 for each session in which they participated; a session lasted no more than an hour.

Data Analyses

Summaries of analyses are tabled in Appendix B. In general, slopes are analyzed following Enns and Rensink's (1991a) procedure. First, simple regression lines for each participant's conditions were fit to target-present and target-absent mean response times (RTs) for correct responses. The average fit of these lines, or the correlation of mean correct RTs with display size, ranges from 0.803 to 1.00 for target-absent displays and .542 to 1.00 for target-present displays across all experiments. Second, the estimated slope parameters are submitted to a repeated-measures ANOVA. Consistent with the within-subject design of the experiments reported, confidence limits for target-present and target-absent conditions are computed using the within-subject error term as recommended by Loftus and Masson (1994). These confidence limits are too narrow to represent graphically and instead are reported in figure legends.

Enns and Rensink (1991a) used Fisher's least-significant difference (LSD) test to determine the reliability of differences between target-present and target-absent slopes associated with a given stimulus condition. However, in view of the fact that more than one comparison is required in some experiments reported here, confidence limits are reported with slopes. In addition, slope ratios are also reported with confidence limits to indicate the probability that search is serial and self-terminating, an explicit prediction of feature-integration theory. Both types of confidence limits, reported in tables, are standard confidence intervals, sensitive to the contribution of every factor involved in the design of a given experiment (Hays, 1963).

A repeated-measures ANOVA is also performed on error rates for each experiment. Although each participant maintained an overall error rate of less than 10%, there are systematic differences in accuracy across conditions and experiments (see Table 1). In particular, target-present trials lead to more errors than did target-absent trials, as is commonly reported (e.g., Goodenough, 1992; Klein & Farrell, 1989). It is important in the present research to note that the error rate tends to increase with speed of response.

Response times are also submitted to a repeated-measures ANOVA, although they are not discussed because predictions are based on slopes. The summaries of analyses for RTs are tabled in Appendix B. Note, however, that the polynomial trends of RT functions computed over display size are reported with the slope data to support predicted main effects and interactions.

EXPERIMENT 1

There were two goals to Experiment 1. The first was to compare performance on a 3D-orientation search task with complete and vertex-only contours as a function of object alignment. Recall that Enns and Rensink (1991a) reported relatively flat search functions with complete contours but not with vertex-only contours. In their experiments, carried out separately for complete and vertex-only conditions, displays were randomly arranged. In the present experiment, using a within-subject design, displays were either aligned or randomly arranged.

The second goal was to extend, to line drawings of 3D objects, Donnelly et al.'s (1991) findings that line drawings of 2D objects can yield parallel search functions from vertices only, based on the colinearity of the vertices. Thus, alignment of 3D objects in a display, like the colinearity of vertices within a display, was expected to result in the parallel processing of 3D orientation. Again, the benefits of object alignment should obtain because of the ensuing periodicity across the entire display (Julesz, 1984; Sagi & Julesz, 1985). Thus, the hypothesis that object alignment plays a role in the parallel recovery of 3D orientation was tested by comparing performance for stimuli consisting of a random array of 3D blocks, as per Enns and Rensink's manipulation, against stimuli in which the 3D blocks were aligned horizontally and vertically.

Table 1

Error Rates (in percentages) across Experiments and Conditions.

	Target present				Target absent			
	Session				Session			
	1	2	3	4	1	2	3	4
Orientation-difference tasks								
Experiment 1								
Randomly-arranged displays								
Complete	3.3	.	.	.	1.0	.	.	.
Vertex-only	3.7	.	.	.	1.0	.	.	.
Aligned displays								
Complete	14.4	.	.	.	3.0	.	.	.
Vertex-only	14.9	.	.	.	3.6	.	.	.
Experiment 2 (randomly-arranged, complete contours)								
	8.8	.	.	.	3.4	.	.	.
Experiment 3 (complete contours only)								
Random	3.5	4.1	3.9	4.0	2.2	2.9	2.8	2.6
Aligned	3.3	3.6	4.5	4.6	3.2	2.7	3.1	3.3
Experiment 4 (aligned vertex-only contours)								
	8.6	9.2	8.8	7.1	1.2	1.1	1.3	1.6

Table 1 (continued)

	Target present				Target absent			
	Session				Session			
	1	2	3	4	1	2	3	4
Inconsistent-vertex tasks								
Experiment 5 (randomly-arranged displays only)								
2-line vertex	4.8	4.9	4.3	4.3	1.5	1.3	1.2	1.3
3-line vertex	11.2	8.1	8.2	9.8	1.3	1.3	1.4	1.1
Experiment 6 (2-line vertices, randomly-arranged)								
	5.8	6.0	5.0	5.9	1.1	1.3	1.7	1.5
Experiment 7 (2-line vertices, randomly-arranged)								
2D contours	8.2	9.1	9.6	9.2	2.3	1.7	2.5	3.0
3D contours	14.1	13.4	14.1	13.7	2.4	1.8	2.2	2.5
Modified 3D	8.9	11.1	11.2	11.3	1.4	2.3	2.9	2.6

Note. The error rates reported are collapsed over display sizes.

To summarize, the following pattern of results were expected. First, the pattern of results obtained by Enns and Rensink (1991a) is expected to replicate, with complete contours resulting in relatively flat search functions compared to vertex-only contours. Second, if closure of contour with vertex-only stimuli is computed in parallel across all objects in the display, then search for a 3D orientation difference is expected to be equivalent for complete and vertex-only contours. In contrast, if closure of contour is computed in parallel for a single object at a time, then search with vertex-only contours is expected to yield serial functions. Third, the influence of alignment on search is expected to be independent of contour completeness. That is, if alignment of objects generates an emergent feature of the display as a whole, then the type of object in a stimulus is not predicted to interact with alignment condition. Finally, randomly-arranged displays, however, are predicted to result in search patterns dependent on whether closure of contour is derived in parallel from vertex-only contours.

Method

Stimuli and Design. The stimuli consisted of displays in which the target, whenever present, was defined by a difference in depicted 3D orientation. Complete and vertex-only contours were presented, either randomly or aligned (see Figures 5 & 6). The experimental design was a 2 (Target Presence: Present or Absent) X 2 (Completeness: Complete or Vertex-only contours) X 2 (Alignment: Random or Aligned displays) X 3 (Display Size: 2, 6, or 12 items) within-subject design. The 576 trials of a single session resulted in 24 trials for each cell of the experimental design.

Subjects. None of the eight participants (four females) had taken part in visual-search tasks in the lab before this experiment. Participants completed a single session.

Results and Discussion

Mean RTs for correct trials are plotted as a function of display size in Figure 8 for randomly-arranged and aligned stimuli separately. Examples of the complete and vertex-only objects are represented at the top of the figure, with the target on the left and a nontarget on the right. The most striking aspect of the data is the absence of relatively flat functions for any of the conditions. In short, there is no evidence of parallel recovery of 3D orientation in any of the conditions. In fact, 2:1 slope ratios between target-absent and target-present trials (see Table 2) suggest the use of serial search processes for every condition. However, and as predicted, displays consisting of vertex-only contours (depicted as dotted lines in Figure 8) yield steeper slopes than do displays with complete contours (depicted as complete lines in Figure 8). Search rates are also influenced by the alignment of 3D blocks, but not in the

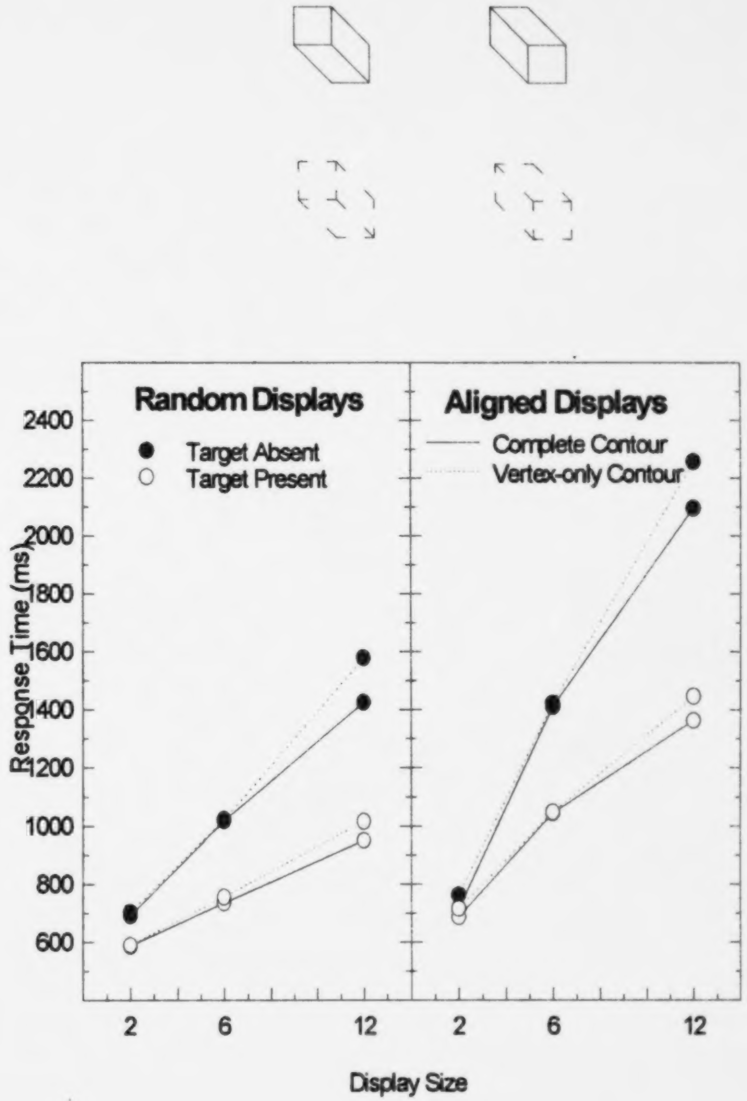


Figure 12. Search functions for randomly-arranged and aligned stimuli of complete and vertex-only contours in Experiment 1 (CL = ± 9.07 ms). Stimulus conditions were randomly presented across trials.

Table 2

Search Slopes (in ms/item) across Conditions of Experiment 1.

	Target present	CI (95%)	Target absent	CI (95%)	Ratio	CI (95%)
Randomly-arranged displays						
Complete	36.2	29.3 to 43.1	72.8	59.1 to 86.6	2.23	1.68 to 2.77
Vertex-only	42.8	35.4 to 50.1	88.0	75.1 to 100.9	2.30	1.70 to 2.91
Aligned display						
Complete	66.5	52.3 to 80.8	136.3	108.3 to 164.3	2.20	1.77 to 2.63
Vertex-only	72.5	57.8 to 87.3	148.6	119.6 to 177.5	2.18	1.83 to 2.54

manner predicted. That is, randomly-arranged displays result in shallower slopes than do aligned displays. These observations are supported by the following statistical analyses.

Slopes. The basic finding is that the search for a 3D-orientation difference does not occur as rapidly with complete contours in this study as was reported by Enns and Rensink (1991a, 1991b), but the obtained slope ratios are similar to theirs, thus partially replicating their findings. Indeed, complete and vertex-only contours behave similarly across studies, with shallower search function for complete-contour displays than for vertex-only displays (77 compared to 38 ms/item; $F(1, 15) = 16.11$, $MS_e = 199$, $p < .001$).

A comparison of slopes between target-present and target-absent trials (see Table 2) suggests that the displays are processed according to serial-processing predictions made by feature-integration theory. Overall, target-present slopes are approximately half the magnitude of target-absent slopes (55 and 111 ms/item, respectively; $F(1, 15) = 69.49$ $MS_e = 1492$, $p < .001$). Slope ratios are statistically equivalent to a 2:1 ratio (confidence intervals are reported in Table 2) in every condition. Although slope ratios fit feature-integration theory, the joint effect of target presence and alignment ($F(1, 15) = 23.14$, $MS_e = 353$, $p < .001$) on slopes contradicts Treisman's argument that alignment only influences mean RTs (Treisman & Gelade, 1980; Treisman & Sato, 1990). In fact, slopes are greater for aligned displays than for randomly-arranged displays (106 vs. 60 ms/item, respectively; $F(1, 15) = 34.42$, $MS_e = 1969$, $p < .001$). The effect is not, however, in the predicted direction.

The polynomial trends of RT functions computed over display size are consistent with serial self-terminating search patterns associated with conjunction searches. The obvious linear component of display size in Figure 8 ($F(1, 15) = 182.61$, $MS_e = 244523$, $p < .001$) accounts for 99.7% of the variance due to display size. The linear component interacts with target presence ($F(1, 15) = 75.20$, $MS_e = 69610$, $p < .001$), with completeness ($F(1, 15) = 15.66$, $MS_e = 8904$, $p < .001$), with alignment ($F(1, 15) = 35.81$, $MS_e = 99206$, $p < .001$), as well as with the combination of target presence and alignment ($F(1, 15) = 24.28$, $MS_e = 17328$, $p < .001$). All but one of these interactions account for more than 99.6% of the variance in the corresponding effects. The interaction of completeness and display $\text{size}_{\text{linear}}$ accounts for 64.7% of the variance. The remaining variance (35.3%) is attributable to a reliable completeness by display $\text{size}_{\text{quadratic}}$ component ($F(1, 15) = 9.29$, $MS_e = 8177$, $p < .008$).

Error rates. Error rates range from 0 to 28.9% across conditions (see Table 3). Completeness of contour does not influence accuracy, nor does it interact with other factors

Table 3

Error Rates (in percentages) across Conditions of Experiment 1.

	Target present			Target absent		
	Display size			Display size		
	2	6	12	2	6	12
Randomly-arranged displays						
Complete contours	1.04	2.61	6.25	0.78	1.04	1.04
Vertex-only contours	0.26	2.60	8.33	2.08	0.00	1.04
Aligned displays						
Complete contours	1.82	12.50	28.91	0.78	3.91	3.39
Vertex-only contours	3.39	16.41	25.00	2.60	2.86	5.47

in this regard. As can be seen in Table 3, error rates are essentially constant across display sizes for target-absent displays, but increase with display size for target-present displays ($F(2, 30) = 41.21$, $MS_e = 1646$, $p < .001$). The main effects of display size ($F(2, 30) = 36.62$, $MS_e = 2234$, $p < .001$) and target-presence ($F(1, 15) = 54.26$, $MS_e = 4717$, $p < .001$) are consistent with the interaction. This pattern of errors suggests that a default target-absent response is adopted by participants; a greater chance of missing the target object is associated with larger display sizes. The error rates also suggest that a response threshold to terminate the search is set (e.g., after a certain percentage of the objects in the display have been scanned) such that more errors occur with target-present displays than with target-absent displays (Cave & Wolfe, 1990; Sternberg, 1966; Townsend, 1990).

The effects of object alignment on accuracy are of particular interest. As noted earlier, the alignment of objects was predicted to generate a periodical texture that would result in parallel target detection (Bergen & Julesz, 1983; Sagi & Julesz, 1985). Contrary to this prediction, error data show that target detection is more accurate with randomly-arranged displays than with aligned displays ($F(1, 15) = 50.08$, $MS_e = 4261$, $p < .001$). Both the interaction of alignment with display size ($F(2, 30) = 23.72$, $MS_e = 880$, $p < .001$), and the interaction of alignment with target presence ($F(1, 15) = 40.29$, $MS_e = 1937$, $p < .001$) influence accuracy in the task. The three-way interaction ($F(2, 30) = 18.73$, $MS_e = 425$, $p < .001$) shows a larger increase in errors across display size for aligned target-present displays than for other conditions. These results suggest that alignment of objects does not always make search easier, but can in some instances make it more difficult, especially with large displays. The criterion might vary with display alignment because the emergent feature generated by the alignment of objects might increase the confidence of observers to respond that the target is present or not. In turn, the increased confidence would bring down the number of objects searched. The effect of display size can be attributed to the fact that the number of objects not searched because of the criterion is proportional to the number of objects in the display. A larger number of unattended objects would lead to a greater number of errors.

Finally, the observed pattern of results is consistent with the view that the serial process involved in search is guided by a response threshold (Cave & Wolfe, 1990). A criterion threshold would prevent an exhaustive search of target-absent trials, but could potentially result in a relatively large number of errors committed on target-present trials when set too low (also see Townsend & Ashby, 1983). Error rates on target-present trials would vary with the stringency of the search criterion.

EXPERIMENT 2

One obvious question to address is why randomly-arranged complete-contour displays do not yield the search functions of similar magnitude as those reported by Enns and Rensink (1991a). As this finding was unexpected, the goal of the present experiment is to replicate as precisely as possible Enns and Rensink's procedure to see whether a 3D orientation difference is detected in parallel based on information obtained from line drawings depicting 3D objects. It is possible that the blocked presentation format used by Enns and Rensink is necessary to observe relatively flat search functions. Thus, in this experiment, only the randomly-arranged displays of complete-contour objects from Experiment 1 were used to replicate their findings.

Method

Stimuli and Design. All stimuli consisted of randomly-arranged, complete-contour objects. Stimuli were similar to those used by Enns and Rensink (1991a), differing only in the degree of displacement of objects from the center of their respective grid cell, as described in the General Methods.

The experimental design was a 2 (Target Presence: Present or Absent) X 3 (Display Size: 2, 6, or 12 items) within-subject design. A total of 576 trials, presented in a single session, yielded 96 trials per condition. Note that the number of trials per condition is slightly more than the number of trials used by Enns and Rensink.

Subjects. The 16 participants (8 females) were naive to the purpose, design, task, and stimuli of this experiment.

Results and Discussion

Mean correct RTs are plotted as a function of display size in Figure 9. The search functions for randomly-arranged complete contours of Experiment 1 are also plotted in Figure 9 for comparison. There is still no evidence of parallel recovery of 3D orientation from line drawings when the design corresponds to Enns and Rensink's (1991a). In short, displays seem to have been searched serially to detect a difference in 3D orientation. Statistical analyses confirm this point and provide further support for feature-integration theory with respect to conjunctive search of 3D orientation from line drawings.

Slopes. Again, the pattern of results partially replicated Enns and Rensink; however, the slopes obtained in this experiment do not approach the values reported by Enns and Rensink. The difference between target-present (27 ms/item) and target-absent (39 ms/item) search rates is reliable ($F(1, 15) = 12.96$, $MS_e = 93.3$, $p < .003$); however, neither of the slopes approaches the values reported by Enns and Rensink (7 and 12 ms/item,

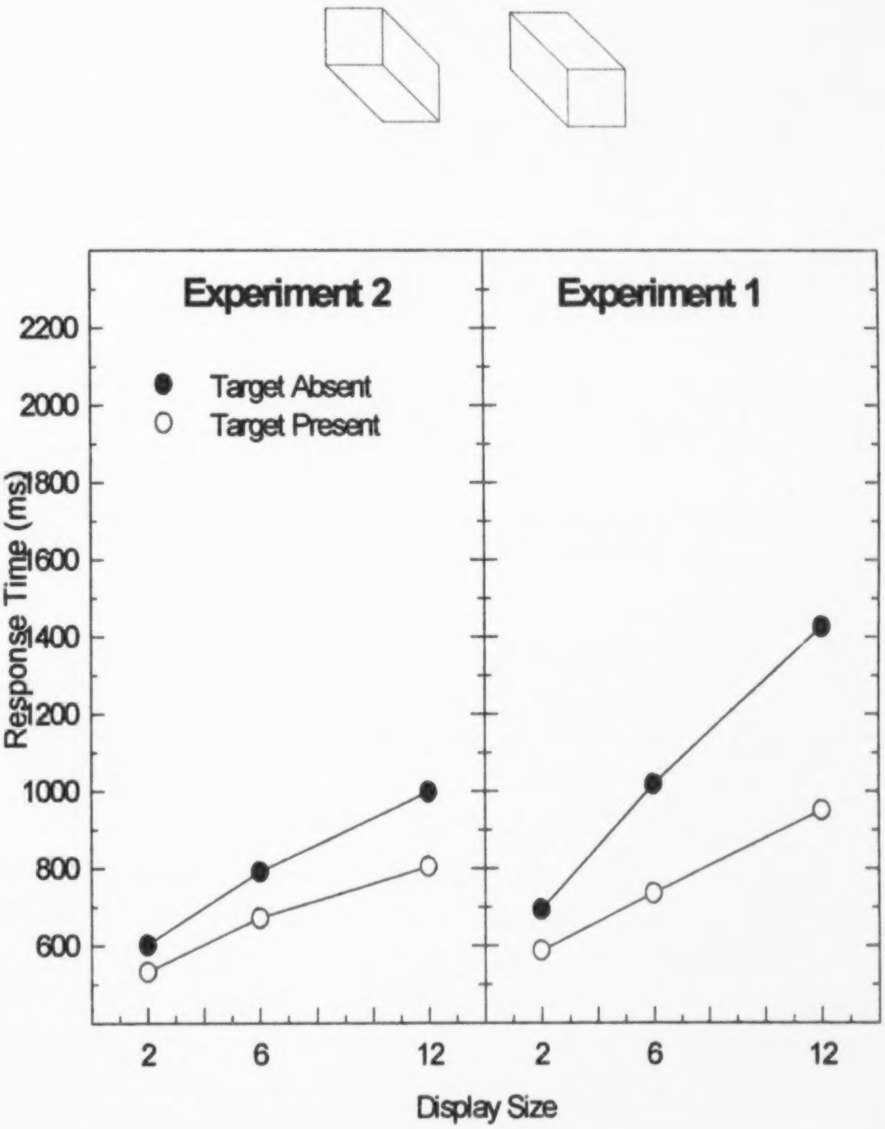


Figure 9. Search functions for a 3D-orientation difference with complete contours. The left panel is for blocked presentation of Experiment 2 (CL ± 7.12) and the right panel is for random presentation (complete contours, randomly-arranged trials only) of Experiment 1 (CL = ± 9.07 ms).

respectively). In addition, the slope ratio between target-present and target-absent trials is 1.40:1. Statistically, this ratio is smaller than the 2:1 ratio predicted by serial-search models ($\text{CI}_{(95\%)}$ is 1.20 to 1.59 ms/item).

As Figure 9 clearly illustrates, the linear component of the RT functions computed over display size is reliable ($F(1, 15) = 53.41$, $MS_e = 33410$, $p < .001$) and accounts for all of the variance due to display size. The linear component of the interaction of target presence and display size is also reliable ($F(1, 15) = 12.64$, $MS_e = 4792$, $p < .003$), itself accounting for 98.6% of the variance of the interaction. These linear trends confirm that participants use visual-search strategies in line with Treisman's (1988, 1993) notion of conjunctive search to perform the task. But more importantly, a comparison of Experiments 1 and 2 supports the notion of a continuum of processing. That is, blocked presentation in Experiment 2 reduced search slopes relative to slopes of Experiment 1.

Error rates. More errors are committed on target-present trials than on target-absent trials ($F(1, 15) = 80.46$, $MS_e = 5.7$, $p < .001$; see Table 4) and further, the number of errors increases with display size ($F(1, 15) = 55.49$, $MS_e = 9.2$, $p < .001$). The interaction of the two factors on error rates is reliable ($F(2, 30) = 59.18$, $MS_e = 9.4$, $p < .001$), with the greatest number of errors committed on 12-item, target-present trials. As with error rates observed in Experiment 1, these results are consistent with the view that a response threshold prevents an exhaustive search (Cave & Wolfe, 1990).

EXPERIMENT 3

Performance in Experiment 1 was contrary to the prediction that alignment increases the periodical surface texture that would in turn facilitate search (e.g., Bergen & Julesz, 1983). Although the experimental factors influenced search rates in Experiments 1 and 2, there is no evidence of parallel recovery of 3D orientation from line drawings within any of the conditions. Results from Experiments 1 and 2 suggest that 3D orientation is not processed in parallel based on information obtained from line drawings, regardless of contour completeness. However, some differences between the present experimental design and Enns and Rensink's (1991a) design are worth closer scrutiny.

Two factors could account for the absence of parallel visual search in Experiments 1 and 2. The first is the blocking of conditions used by Enns and Rensink, which was not done in Experiment 1. However, Experiment 2 took this factor into account and still failed to produce evidence of parallel processing. The second reason for a difference in results between Experiment 1 and Enns and Rensink's results is the possibility that familiarity,

Table 4

Error Rates (in percentages) across Conditions of Experiment 2.

	Display size		
	2	6	12
Target absent	4.17	2.73	3.45
Target present	1.24	5.34	16.93

through practice, enhanced the performance of Enns and Rensink's participants (see Shiffrin & Schneider, 1977). With respect to familiarity, Experiment 1 differs from Enns and Rensink on two counts. First, the number of trials presented differs (40 to 60 trials per experimental condition in Enns & Rensink compared to 24 trials in Experiment 1). This difference, however, was also counteracted in Experiment 2 with a fourfold increase in the number of trials compared to the number of trials in Experiment 1. Although the slopes were reduced, as suggested by the notion of a continuum of processing, the greater number of trials did not lead to parallel processing of 3D orientation in Experiment 2. Second, half of the participants recruited by Enns and Rensink were practiced observers who routinely participated in visual-search experiments; in Experiments 1 and 2, only naive participants were recruited. The difference in familiarity with the task could account for the development of more efficient search strategies by participants in Enns and Rensink's study (Shiffrin & Schneider, 1977).

To assess the possible influence of blocked presentation and familiarity on performance, participants in Experiment 3 were recruited from those subjects who had participated in one of the prior experiments and they completed the task over four sessions with blocked conditions. The predictions are similar to those of Experiment 1; namely, that after extended practice with the task, participants will produce relatively flat search functions with complete-contour displays. This prediction is consistent with the notion of a continuum of processing. Note that vertex-only contours were not used in Experiment 3 because the finding of relatively flat search functions with complete contours still requires replication. Finally, alignment of objects is predicted to yield shallower search functions compared to randomly-arranged displays, when trials are blocked on alignment (i.e., a between-subjects factor).

Method

Stimuli and Design. Only complete-contour displays are presented in this experiment. Furthermore, half of the participants are presented aligned displays and the other group of participants are presented randomly-arranged displays. The design of the experiment is a 2 (Target Presence: Present or Absent) X 3 (Display Size: 2, 6, or 12 items) X 4 (Sessions) X 2 (Alignment: Random or Aligned displays) mixed design, with the last factor as a between-subjects factor. In total, each participant is presented 2304 trials. These trials result in 96 trials per condition across the four experimental sessions.

Procedure. Participants completed four sessions within 4 days. Instructions were read at the start of the first experimental session only. Before each session, practice trials were given and participants were reminded to respond as rapidly and as accurately as possible. In all other respects, the procedure was the same as in Experiment 1.

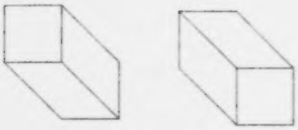
Subjects. Sixteen participants (8 females) were assigned to one of the two alignment conditions: either randomly arranged or aligned. In contrast to Experiment 1, all participants had previously taken part in a visual-search task. Participants returned to the laboratory four times over the course of 4 days.

Results and Discussion

Mean RTs for correct trials for sessions 1 and 4 are plotted as a function of display size in Figure 10 for randomly-arranged and aligned trials separately. The effect of object alignment on search is now in the predicted direction. Aligned displays show shallower slopes across display sizes than do randomly-arranged displays. However, search functions are not consistent with patterns expected from parallel processing across all conditions. For example, relatively shallow slopes are observed only in the last two sessions with randomly-arranged displays. Furthermore, slope ratios remain within a 2:1 range, as predicted by notions of self-terminating serial search. Thus, these data provide only a partial extension of Enns and Rensink's conclusions. These observations are substantiated by the following statistical analyses.

Slopes. Briefly, the alignment of objects showed an important decrease in search slopes as of the first session with aligned displays, whereas randomly-arranged displays required three sessions to show comparable search functions. The interaction of alignment and session ($F(3, 42) = 2.99$, $MS_e = 78.6$, $p < .09$) is reflected in the relatively large decrease in slopes across sessions for aligned displays (see Table 5). Furthermore, the interaction of target presence by session ($F(3, 42) = 5.19$, $MS_e = 33.7$, $p < .03$) shows a different response pattern across sessions for target-absent than for target-present trials: The reduction in slope is larger across sessions for target-present than for target-absent trials. Alignment of objects also plays an important role in the development of efficient processing for this task. The pattern of slopes reveals a reliable effect of alignment ($F(1, 14) = 5.91$, $MS_e = 1612$, $p < .03$), with shallower slopes for aligned displays than for randomly-arranged displays (20 vs. 37 ms/item, respectively). In addition, there is a reliable effect of target presence ($F(1, 14) = 27.07$, $MS_e = 477$, $p < .001$), with shallower slopes for target-present trials (18 ms/item) than for target-absent trials (38 ms/item).

It is interesting to note that with increased familiarity across sessions, the search rates show a significant decrease ($F(3, 42) = 36.52$, $MS_e = 78.6$ $p < .001$), but slope ratios still fall within limits of a 2:1 ratio (see Table 5), except in the third session with aligned



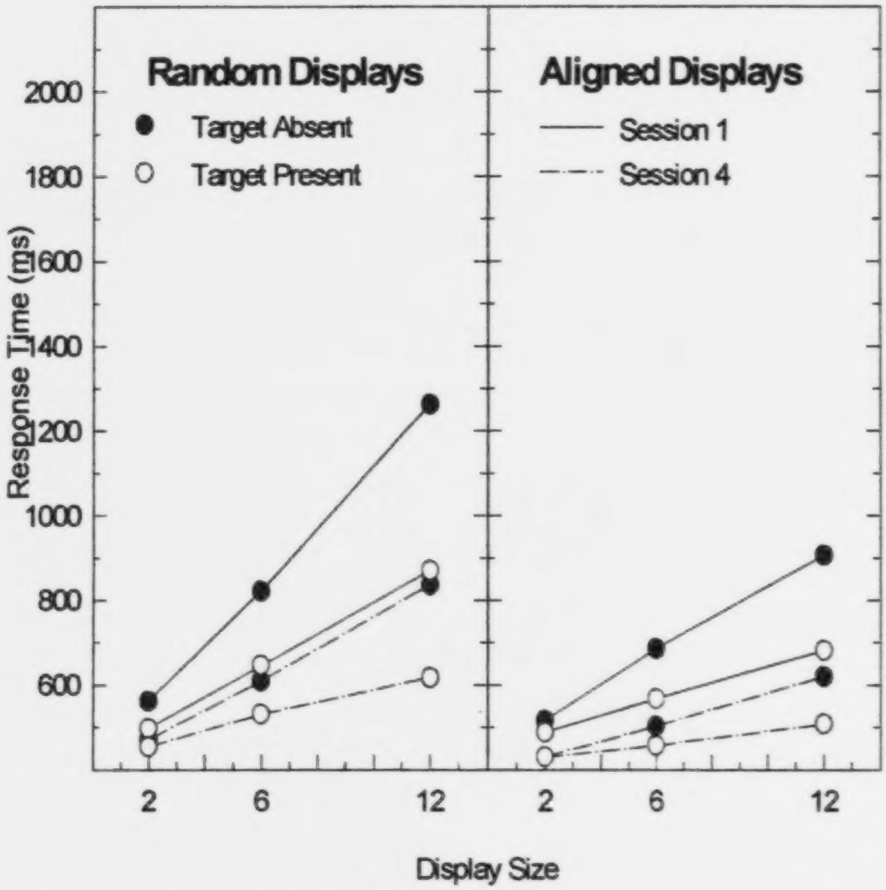


Figure 10. Search functions for aligned and randomly-arranged stimuli (blocked presentation) in the first and last sessions of Experiment 3 (CL = ± 5.55 ms).

Table 5

Search Slopes (in ms/item) across Conditions and Sessions of Experiment 3.

	Target present	CI (95%)	Target absent	CI (95%)	Ratio	CI (95%)
Randomly-arranged displays						
Session 1	37.2	26.3 to 48.1	70.3	41.7 to 99.0	1.83	1.53 to 2.12
Session 2	25.2	18.0 to 32.4	50.6	31.5 to 69.7	1.97	1.70 to 2.24
Session 3	20.0	13.3 to 26.8	39.8	20.6 to 59.0	1.93	1.50 to 2.35
Session 4	16.2	10.7 to 21.7	36.7	20.5 to 52.8	2.30	1.50 to 3.10
Aligned displays						
Session 1	19.3	12.8 to 25.7	38.8	17.2 to 60.5	2.01	1.26 to 2.75
Session 2	11.9	7.3 to 16.4	28.3	16.4 to 40.2	2.46	1.91 to 3.01
Session 3	9.0	5.3 to 12.7	23.8	12.8 to 34.7	2.77	2.21 to 3.33
Session 4	7.9	5.7 to 10.0	19.0	9.7 to 28.3	2.29	1.57 to 3.01

displays. The pattern of search across sessions is reminiscent of Townsend and Ashby's (1983) notion of limited parallel-processing capacity. Briefly, this notion holds that some information is processed in parallel, for example information pertinent to a single object in the display, but information across multiple objects in the display is processed serially. The improvement in performance across sessions is therefore likely due to an improvement in the processing efficiency between elements in the display. These effects suggest that (1) search processes are probably serial in nature and (2) relative differences in search slopes across sessions reflect quantitative, but not necessarily qualitative, changes in processing. I will return to this argument when discussing the results of the first four experiments.

The linear functions describing search times across display sizes support the conclusions that visual search for a 3D-orientation difference depends on the serial processing of objects in a display. These trends provide additional evidence that the displays are not processed in parallel. The linear component of display size accounts for 98.8% of the variance for this factor ($F(1, 14) = 64.79$, $MS_e = 79609$ $p < .001$). The display size$_{\text{linear}}$ component interacts with target presence, accounting for 97.1% of the interaction's variance ($F(1, 14) = 27.13$, $MS_e = 23476$, $p < .001$). In addition, the linear component of display size interacts with alignment ($F(1, 14) = 6.03$, $MS_e = 79609$, $p < .03$), accounting for 99.2% of the variance.

Error rates. Error rates range from 1.2 to 7.9% across conditions (see Table 6). There are no reliable influences of session or alignment on accuracy. However, alignment interacts with both target presence and display size ($F(2, 28) = 6.37$, $MS_e = 11.0$, $p < .02$). There are more errors committed across display sizes with target-present trials than with target-absent trials, and more of these errors are associated with aligned displays than with randomly-arranged displays. Reliable main effects of target presence ($F(1, 14) = 4.74$, $MS_e = 23.4$, $p < .05$), of display size ($F(2, 28) = 22.98$, $MS_e = 17.1$, $p < .001$), and of their interaction ($F(2, 28) = 5.74$, $MS_e = 11.0$, $p < .03$) on accuracy are observed.

EXPERIMENT 4

The prediction that alignment of objects would facilitate search is supported in Experiment 3. However, even though search rates decrease over sessions for both randomly-arranged and aligned displays, Enns and Rensink's (1991a) results are not entirely replicated with the randomly-arranged displays. That is, slopes are not within the range of values reported by Enns and Rensink. The present data, together with those of Enns and Rensink, clearly demonstrate that a continuum of processing might best characterize search performance.

Table 6

Error Rates (in percentages) across Conditions and Sessions of Experiment 3.

	Target present			Target absent		
	Display size			Display size		
	2	6	12	2	6	12
Randomly-arranged displays						
Session 1	1.30	1.82	7.42	2.08	2.47	2.08
Session 2	1.43	2.86	7.94	2.34	2.34	4.17
Session 3	1.17	4.17	6.25	1.56	3.38	3.39
Session 4	1.17	3.00	7.94	1.43	3.91	2.61
Aligned displays						
Session 1	3.12	1.56	5.08	2.87	2.34	4.30
Session 2	3.13	1.30	6.25	1.17	1.95	4.95
Session 3	4.82	2.60	5.99	2.08	1.43	5.86
Session 4	4.04	3.00	6.90	1.30	3.12	5.34

Search functions equivalent to those reported by Enns and Rensink (i.e., slopes in the range of 7 ms/item and 12 ms/item for target-present and target-absent trials, respectively) were obtained only with aligned displays. An important difference between the randomly-arranged displays in Experiment 3 and those in Enns and Rensink is the displacement value used to randomize the arrangement of objects in a display. Enns and Rensink used a displacement value of 0.5° of visual angle, whereas the value is much larger (2.5°) in Experiment 3. The difference can be interpreted in terms of the relative displacement of objects compared to the size of the object. In Enns and Rensink's study, the ratio of displacement to size is 0.33. In the present research, the ratio is 1.66. The difference between these two measures suggests that, although Enns and Rensink disrupted the alignment of objects, it is possible that their displays were functionally aligned and that alignment facilitated performance.

The relative difference in search slopes as a function of object alignment suggests that the search for 3D orientation is a function of (1) an emergent feature generated by the alignment of objects in the displays, (2) the need to develop an efficient process to detect a 3D orientation difference, and (3) the effect of mixing conditions in Experiment 1, which apparently made it more difficult to achieve such an efficiency. More precisely, object alignment fosters the development of a precise location algorithm, enabling search to move rapidly from one object to the other. Furthermore, participants might require a certain amount of practice with the different conditions to elaborate an efficient algorithm for search, because objects are in different locations as a function of display size. Finally, blocked presentation might be more conducive to the elaboration of the search algorithm based on location compared to randomized presentation as in Experiment 1. In fact, the pattern of results in Experiment 3 suggests that it is possible to reduce search slopes with aligned displays or with repeated practice on the task with randomly-arranged displays. The reduction in slopes could be due to the honing of processes required for very rapid, but still serial, recovery of 3D orientation from line drawings (see Schneider & Shiffrin, 1977; Schneider & Shiffrin, 1977 on learning consistent mapping). More precisely, consistent learning, as a result of searching for the same target from trial to trial, with nontargets arranged in the same configuration (for a given display size), results in the development of automatic processes. Consistent learning could not occur in Experiment 1 because alignment conditions were randomized. Relatively flat search functions obtained with aligned displays are consonant with the notion of a continuum of processing. It is unclear why aligned trials led to stepper search functions than randomly-arranged trials in Experiment 1.

The results of Experiment 3 suggest that the recovery of 3D orientation is influenced by the alignment of objects in a display and that familiarity with the task is needed to develop efficient search processes. Thus, in the present experiment, search for a difference in 3D orientation with vertex-only contours is measured with aligned displays and across repeated sessions, to determine if object alignment and practice will yield relatively rapid search slopes. Under these conditions, the first prediction is that alignment of objects will facilitate processing of the displays. The second prediction is that, independent of the effect of object alignment, search for a 3D orientation difference should improve across sessions and approximate slopes obtained with complete contours in Experiment 3.

Method

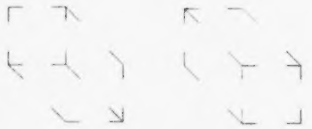
Stimuli and Design. Stimulus items consist of vertex-only contours depicting 3D blocks identical to those used in Experiment 1. Only aligned displays are used in this experiment. The experimental design is a 2 (Target Presence: Present or Absent) X 3 (Display Size: 2, 6, or 12 items) X 4 (Sessions) within-subject design. Thus, each participant could potentially contribute 96 correct responses to each experimental condition.

Subjects. The eight participants (4 females) had previously taken part in one visual-search experiment from this research program before this experiment.

Results and Discussion

Mean RTs for correct trials of the first and last sessions are plotted as a function of display size in Figure 11. Although search functions are steeper than the ones obtained for complete contours in Experiment 3, search for a 3D-orientation difference with vertex-only contours produce search functions interpreted as evidence of serial processing. This is the case even though the depicted objects in a display are aligned and participants are given an opportunity to become familiar with the task. This finding suggests that contour completion, like repeated practice and object alignment, leads to graded search slopes. Recall that practice and alignment of objects are apparently responsible for the relatively flat search functions with complete contours in Experiment 3. A closer look at the results of the statistical analyses will show that the recovery of 3D orientation from vertex-only contours is best described by arguments of conjunctive search proposed by feature-integration theory.

Slopes. Even though there is a reliable decrease in search slopes across the four sessions ($F(3, 21) = 9.33$, $MS_e = 411$, $p < .003$), the magnitude of the slopes refutes any arguments favoring parallel recovery of 3D orientation with vertex-only contours. Slopes (see Table 7) differ as a function of target presence ($F(1, 7) = 50.77$, $MS_e = 1508$, $p < .001$), with target-present trials having a shallower slope than do target-absent trials (69 vs. 138



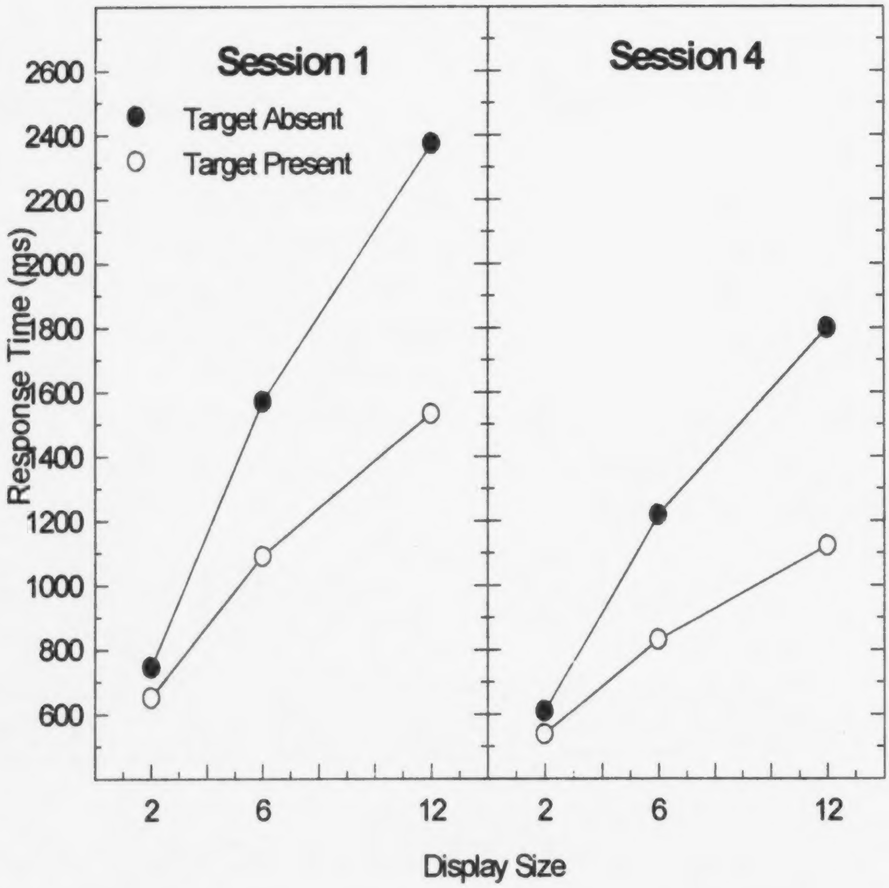


Figure 11. Search functions for a 3D-orientation difference with aligned displays of vertex-only contours in the first and last sessions of Experiment 4 (CL = ± 8.69 ms).

Table 7

Search Slopes (in ms/item) across Sessions of Experiment 4.

	Target present	CI (95%)	Target absent	CI (95%)	Ratio	CI (95%)
Session 1	87.0	58.2 to 115.8	160.6	113.9 to 207.4	1.93	1.59 to 2.27
Session 2	71.2	45.8 to 96.6	144.5	92.1 to 197.0	2.03	1.87 to 2.18
Session 3	62.7	42.7 to 82.7	132.9	94.2 to 171.6	2.22	1.74 to 2.70
Session 4	57.7	40.5 to 75.0	117.2	87.0 to 147.5	2.13	1.72 to 2.54

ms/item, respectively). Even though the 2:1 slope ratios between target-absent and target-present trials reported, with confidence intervals, in Table 7 provides support for a serial-search argument, the reduction in slopes across sessions is consistent with the hypothesis of a continuum of processing.

As was found in Experiment 3, search times across display sizes are best described as linear functions. More than 96% of the variance is accounted for by linear functions for display size ($F(1, 7) = 56.19$, $MS_e = 637057$, $p < .001$), and for the interaction of display size with target presence ($F(1, 7) = 53.86$, $MS_e = 72758$, $p < .001$).

Error rates. Error rates across display sizes and conditions are reported in Table 8. A larger number of errors are committed on target-present, 12-item trials than in any other condition. As with previous experimental results, the effects of target presence ($F(1, 7) = 70.78$, $MS_e = 34.5$, $p < .001$) and display size ($F(2, 14) = 64.67$, $MS_e = 19.3$, $p < .001$) affect accuracy, as do their interaction ($F(2, 14) = 30.21$, $MS_e = 42.4$, $p < .001$).

The fact that the task is at all possible (viz., low error rates, 1.3% for target-absent trials and 8.4% for target-present trials) indicates that vertices can be used for the recovery of 3D orientation, but that 3D orientation is not recovered in parallel from this information alone. The main effect of session on accuracy is not reliable, but its interactions with target presence ($F(3, 21) = 4.27$, $MS_e = 3.9$, $p < .02$) and with display size ($F(6, 42) = 2.79$, $MS_e = 4.3$, $p < .07$) are also observed. This pattern of results suggests that the response threshold is not fixed and can be modified to fit the difficulty of the search as a function of display size (Cave & Wolfe, 1990).

DISCUSSION OF EXPERIMENTS 1 THROUGH 4

In summary, the idea that 3D orientation is processed in parallel from line drawings of multiple objects is not supported by the results of Experiments 1 through 4. However, when complete-contour line drawings are aligned, a 3D orientation difference can be detected very rapidly (serial search functions with relatively flat slopes). In addition, the results of Experiments 3 and 4 clearly show that search performance improves with repeated practice. If Donnelly et al.'s finding can be extended to 3D object descriptions (i.e., if 3D object descriptions, like 2D object descriptions, can be recovered in parallel from vertex-only contours), then the resulting search pattern in Experiments 3 and 4 can be characterized as a parallel processing of information belonging to a single object and serial processing across objects in a display.

The improvement in search performance in Experiments 3 and 4 can be explained in the following manner. If vertices comprising a single object are processed in parallel, and

Table 8

Error Rates (in percentages) across Sessions of Experiment 4.

	Target present			Target absent		
	Display size			Display size		
	2	6	12	2	6	12
Session 1	0.78	6.64	18.49	0.65	1.69	1.17
Session 2	0.39	6.51	20.83	0.78	1.69	0.91
Session 3	1.04	6.12	19.14	1.04	1.69	1.04
Session 4	1.56	5.21	14.45	1.04	2.86	1.04

search from one object to another in the display depends on serial processes, then the time necessary to process a single object is of little consequence to the total time to process an entire multiple-object display. As a result, it is the serial scanning of the display that accounts for changes in processing time. In this case, the improvement in performance across sessions in Experiments 3 and 4 likely reflects gains in serial processing across objects, rather than an improvement in the parallel construction of object descriptions. Such an account is again consistent with the suggestion that processing occurs along a continuum of processing, as evidence by a reduction in search rates characterized by a consistent slope ratio.

With the exception of results from Experiment 1, the object alignment effect can now also be interpreted according to a continuum of processing account. By aligning objects, all the features in the objects do not need to be searched per se, because a search algorithm, based on an emergent feature of the display, can be set up to locate the distinguishing feature being searched (cf. Cohen & Ivry, 1991). That is, object alignment fosters the use of exact locations to quickly access vertices of the object examined (cf. Treisman & Gelade, 1980 on precueing of location). The algorithm can be set up upon the presentation of the display based on information obtained preattentively from texture characteristics, as suggested by Julesz (1984) and Cavanagh, Arguin, and Treisman (1990). A search algorithm would free up resources needed for other aspects of the search process. Because object alignment is a characteristic of the display (i.e., possibly an emergent feature of the displays) and not a characteristic inherent to 3D orientation of each object, participants would require time to refine a search algorithm designed for 3D orientation per se. The practice effect observed in Experiments 3 and 4 is consistent with this suggestion. Participants in Experiment 1 had neither very much practice nor the opportunity to develop an efficient search strategy due to the random presentation of the conditions. Furthermore, a comparison of search rates observed in the present research and Enns and Rensink's findings bears out the relative effect of alignment on search rates.

The larger proportion of errors in Experiment 1 compared to other experiments suggests that a search algorithm is more easily refined when stimulus presentation is blocked, as in Experiments 2 through 4, than when stimulus presentation is randomized across trials, as in Experiment 1. This idea is consistent with the influence of consistent learning (Schneider & Shiffrin, 1977) on the development of automatic search processes.

The results of the first four experiments indicate that depicted 3D orientation is not a property of line drawings that is readily processed in parallel across objects without a great deal of practice. The spatial relations defining 3D orientation apparently are processed as conjunctions. Another way in which the results of the previous experiments are inconsistent with notions of preattentive processing held by feature-integration theory, as discussed in Experiment 3, is the practice effect observed across sessions. Shiffrin and Schneider (1977) have argued that serial processes can, with practice, become automatized and yield measures of performance similar to those observed with preattentive processes (i.e., relatively flat search functions suggesting parallel processing). They claimed that a set of serial processes can, in some sense, be compiled into a single process. A compiled process would be more efficient (carried out more rapidly) than the aggregate of the serial processes. There is no indication in feature-integration that preattentive processes can result from the compilation of serial processes.

Knowledge that search processes can be refined and used to detect 3D orientation does not, however, clarify what kind of 3D information, if any, is inherently preattentively available from line drawings, or processed in parallel to recover an object description. The argument was made in the introduction that edges and vertices serve a primary function in the recovery of 3D information from line drawings. Therefore, if vertices are processed early in the visual sequence, but do not initially facilitate the recovery of 3D orientation, then the question remains as to what role vertices play, more generally, in the early recovery of object information. Vertices alone are not sufficient for the parallel recovery of 3D orientation even when the displays are aligned as in Experiment 4. Thus, the issues surrounding parallel processing of vertices will no longer be couched in terms of 3D orientation. Rather, the focus of the research will shift according to arguments presented earlier concerning the role of vertices in the recovery of 3D object descriptions from line drawings. Thus, factors expected to affect the detection of a misaligned vertex, as in Donnelly et al.'s task, are examined in Experiments 5 through 7. As suggested by Donnelly et al., the parallel detection of a misaligned vertex among vertices depicting the contour of an object would imply that the object structure is recovered during parallel processing stages.

If vertices can be processed in parallel to derive 3D object descriptions, then deleting line segments between vertices should not affect the parallel processing of vertices. This hypothesis, that vertices in line drawings are used to recover 3D object descriptions, is tested in Experiments 5 through 7. The premises underlying these experiments are that closure of contour is computed in parallel across the visual field (Ullman, 1989), and observers have parallel access to closed-object descriptions at least for single objects (Donnelly et al., 1991). By extension, visual search across objects should be unaffected by the number of objects in a display. Any line segment that is inconsistent with the overall, or global, interpretation suggested by vertices will be easily detected because it will disturb the perceptual grouping of vertices into an object, resulting in the parallel detection of the inconsistency. For this effect to occur, it must be assumed that parts of an object (i.e., vertices) are encoded in parallel.

In summary, the parallel grouping of vertices for the recovery of 3D object descriptions is tested by measuring visual-search performance for displays similar to those of Experiment 4 (also see Enns & Rensink, 1991a, Experiment 6). The stimuli are modified to correspond to the stimuli used by Donnelly et al. (1991) in which one depicted object had a misaligned vertex. A strict prediction, based on the modified feature-integration theory (Treisman, 1991, 1993) is that object descriptions are available from the parallel processing of vertices, and thus will result in the immediate detection of an object with a misaligned vertex embedded in a multiple-object display. Alternatively, the notion of a continuum of processing predicts differences in search rates as a function of vertex organization. That is, the processing of vertices depicting 2D, 3D, and quasi-3D objects are expected to yield search functions commensurate with such vertex organization.

In Experiment 5, the task consists of detecting the presence of a vertex inconsistent with the description suggested by other vertices depicting a 3D object (see Figure 12). The 3D block containing the misaligned vertex is embedded in an array of 3D blocks for which all vertices are consistent with the suggested 3D description. Participants repeated the task over four sessions. In Experiment 6, the stimuli are modified to eliminate any possibility of 3D interpretation. This manipulation is carried out to confirm that the findings in Experiment 5 are not due to the recovery of simpler 2D object descriptions. Finally, in Experiment 7, the design is modified to include, within a single experiment, a direct comparison of depicted 2D and depicted 3D contours from vertices only. A third stimulus type is included in Experiment 7 to control for the difference in the amount of visual information in 2D and 3D contours.

EXPERIMENT 5

The purpose of the first experiment in this series is to determine whether or not a misaligned vertex in a set of vertices representing the contour of a 3D object can be detected rapidly in a multiple-object display. The stimuli consist of line drawings of vertex-only 3D blocks. All objects in a display depict 3D blocks of the same 3D orientation. The observer's task is to decide whether or not one of the vertices in the display is inconsistent with the contour of a 3D block, as in Donnelly et al.'s (1991) task with 2D contours. The main prediction of the present experiment is that colinearity of vertices will enable parallel

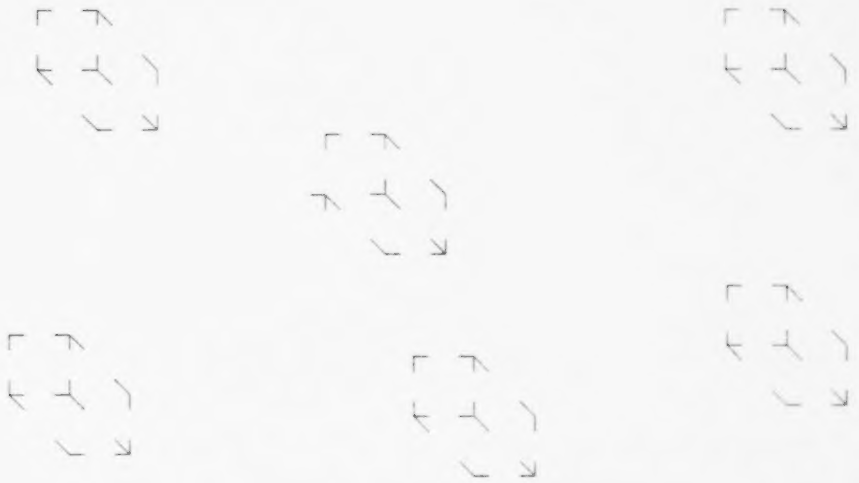


Figure 12. Example of a vertex-only 6-object stimulus with a misaligned vertex. The misaligned vertex is located on the left side of the object in the middle of the top row.

computation of object descriptions and result in the very rapid detection of a misaligned vertex.

Randomly-arranged displays are used to reduce any effect of object alignment per se on performance. That is, this experiment examines the alignment of vertices within an object, not between objects. Consistent with Experiment 4, and thus enabling a comparison of results across experiments, participants completed four sessions within 4 days. However, it is expected that repeated sessions will not affect search performance if a misaligned vertex can be detected in parallel. In other words, the parallel grouping of vertices into object descriptions is expected to yield relatively flat search functions independent of practice.

There have been suggestions that different vertex types convey different information about the structure of an object (e.g., Hummel & Biederman, 1992; Enns, 1992). The stimuli of the present experiment enable an exploration of this proposal (see Figure 13 for targets used in target-present trials). There are two pairs of vertices that are identical with respect to the arrangement of their constituent vertices (except for the overall orientation of the vertices of a pair). One pair consists of 2-line vertices and the other of 3-line vertices. A vertex was made inconsistent by replacing it with its mirror-image, resulting in an misaligned vertex matched for orientation to the other vertex of a pair. In this way, any evidence of parallel processing cannot be attributed to unique characteristics of the misaligned vertex, as suggested by notions of preattentive detection. The misaligned vertex is unique based only on the fact that it is misoriented with respect to the object structure suggested by other vertices. By comparing performance as a function of the type of vertex made inconsistent, the influence of vertex type on contour processing can be confirmed. The two types of vertices are equally distributed among trials.

Method

Stimuli and Design. The vertex-only contours used in Experiment 4 serve as the basis for the stimuli in the present experiment. A target is defined as the object in the display containing a misaligned vertex. A misaligned vertex refers to an outer vertex mirror-imaged about its apex (see Figures 12 & 13). All displays consist of randomly-arranged displays as described in the General Methods. The third independent variable is the type of vertex made inconsistent in target-present displays.

The experimental design is a 2 (Target Presence: Present or Absent) X 3 (Display Size: 2, 6, or 12 items) X 2 (Vertex Type: 2-line or 3-line vertices) X 4 (Sessions) within-subject design. The trial distribution across the four sessions resulted in 48 trials per condition.

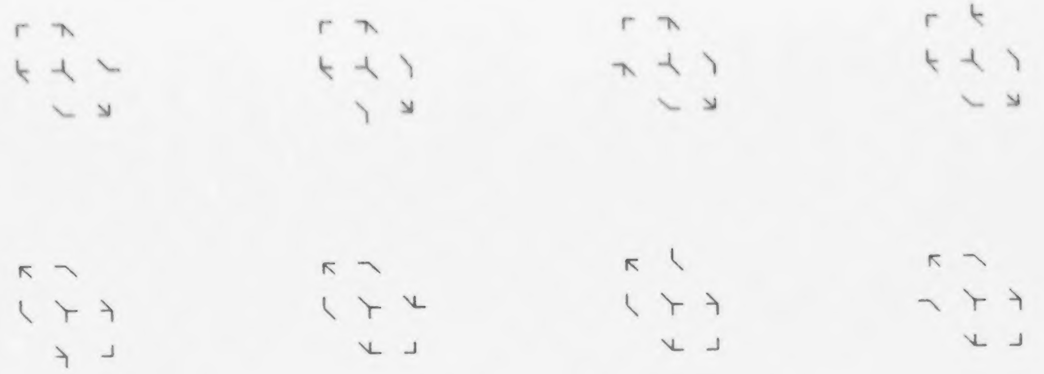


Figure 13. Possible locations of the misaligned vertex in target-present objects. A target-present trial contains one of the above contours as the target. This figure is not an actual stimulus.

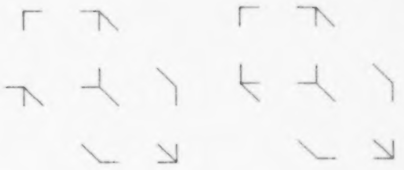
Procedure. The same general procedure is used in this experiment with two exceptions. First, the instructions read to participants were slightly modified (see Appendix A.2) and second, participants were asked to answer five protocol questions after testing.

Subjects. Nine participants (5 females), who had participated in only one previous experiment, were recruited. One female's data were dropped after close scrutiny of the accuracy and RT data: Accuracy is perfect in most conditions and RTs are consistently elevated compared to other participants' search times (i.e., mean correct RTs approximately twice as large as the group average). Furthermore, protocol data suggest that she had deliberately used an exhaustive search strategy to ensure accuracy in performance. Note that the removal of this participant's data improves the likelihood of supporting the hypothesis that vertices are processed in parallel to recover object descriptions in multiple-object displays.

Results and Discussion

Mean correct RTs are plotted as a function of display size in Figure 14. In addition, individual slope data are reported in Table 9. Note that 2-line and 3-line vertices yield equivalent measures of performance and thus are collapsed on the graph of Figure 14, although they are shown individually in Table 10. There are no effects on slopes, or interactions, involving vertex-type. The results of this experiment are commanding because they provide support for the hypothesis that vertices play a fundamental role in the recovery of object descriptions from line drawings of 3D objects. With sufficient practice on the task, participants can detect a misaligned vertex very rapidly. The relatively flat search functions for target-present trials, and corresponding slope ratios greater that 2:1, suggest that vertices can be processed in parallel to derive object descriptions. Furthermore, any role played by alignment of objects, as in Experiment 3, cannot be responsible for the observed effects because all displays consist of randomly-arranged objects. The pattern of results from the following statistical analyses support this claim.

Slopes. There is a main effect of target presence ($F(1, 7) = 64.60$, $MS_e = 1209$, $p < .001$) and of session ($F(3, 21) = 15.60$, $MS_e = 647$, $p < .002$) on slopes. The interaction of these two factors is the only reliable interaction ($F(3, 21) = 9.62$, $MS_e = 427$, $p < .02$) affecting slopes. Target-absent slopes decrease from 104 ms/item to 35 ms/item across the four sessions and target-present slopes drop from 23 ms/item to 7 ms/item (see Table 10). Polynomial trends accounting for display size are restricted to linear functions. The effect of display size was 99.9% linear ($F(1, 7) = 61.12$, $MS_e = 164997$, $p < .001$). This linear function interacts with target presence ($F(1, 7) = 67.70$, $MS_e = 60219$, $p < .001$), accounting



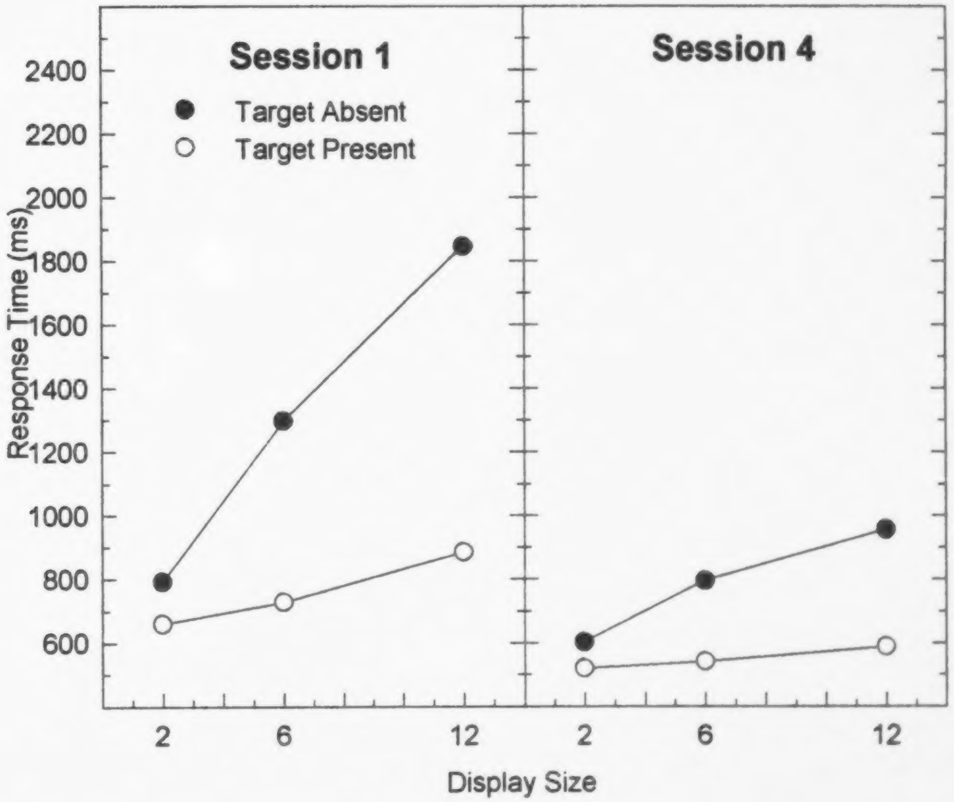


Figure 14. Search functions for a misaligned vertex with 3D contours in the first and last sessions of Experiment 5 (CL = ± 4.17 ms).

Table 9

Individual Search Slopes (in ms/item) for Target-Present and Target-Absent Trials by Session of Experiment 5.

	Target present				Target absent			
	Session				Session			
	1	2	3	4	1	2	3	4
Subject 1	30.7	25.9	19.7	8.9	193.4	95.1	94.4	37.0
Subject 2	33.1	27.0	12.7	5.5	109.8	78.4	61.2	22.8
Subject 3	24.9	22.6	20.5	8.0	105.3	77.7	93.9	59.1
Subject 4	12.5	8.5	3.7	3.8	81.5	46.4	39.8	35.7
Subject 5	25.8	13.2	9.3	6.9	72.6	57.7	55.6	47.3
Subject 6	67.5	8.5	12.2	6.0	82.8	27.4	33.6	19.7
Subject 7	26.6	17.4	19.9	15.8	56.0	52.8	82.5	50.0
Subject 8	2.3	-0.9	6.2	0.0	62.4	24.0	23.8	3.4
Mean	27.9	15.3	13.0	6.9	95.5	57.4	60.6	34.4
Std dev.	17.7	9.1	6.1	4.3	41.0	23.5	25.7	17.1

Table 10

Search Slopes (in ms/item) across Vertex Types and Sessions of Experiment 5.

	Target present	CI (95%)	Target absent	CI (95%)	Ratio	CI (95%)
2-line vertex						
Session 1	22.9	15.0 to 30.8	106.1	71.0 to 141.2	6.01	2.53 to 9.50
Session 2	16.8	7.8 to 25.8	59.1	41.6 to 76.8	1.03	-4.84 to 6.89
Session 3	14.8	9.1 to 20.4	57.4	35.9 to 78.8	4.10	2.77 to 5.42
Session 4	8.4	4.5 to 12.3	34.6	19.1 to 50.0	3.80	2.52 to 5.08
3-line vertex						
Session 1	26.1	17.8 to 34.3	108.4	70.9 to 146.0	4.52	2.92 to 6.13
Session 2	17.8	11.2 to 24.5	64.3	46.6 to 82.1	3.92	2.80 to 5.04
Session 3	13.5	8.7 to 18.3	67.9	43.1 to 92.7	5.24	3.63 to 6.86
Session 4	6.3	1.7 to 10.9	38.9	25.4 to 52.4	13.04	1.86 to 24.22

Note. It is problematic to interpret mean ratios when an individual subject's ratio is computed on the basis of a target-present slope smaller than 1.0 ms/item. Therefore, two subjects with target-present slopes smaller than 1.0 ms/item were not included in the computation of means for slopes, ratios and confidence intervals. If these subjects were included, the data and their interpretation would be skewed. For example, if the data from the one subject not considered in Session 1 for 3-line vertex were in fact included (slopes = 0.05 and 58.8 ms/item for target-present and target-absent slopes), that subject's slope ratio would be 117.60. These values would decrease the mean slopes (22.9 and 102.2 ms/item, respectively) and the mean slope ratio would increase to 18.66. The corresponding confidence intervals would be narrowed for the mean slopes (13.0 to 32.8 and 67.8 to 136.7 ms/item for target-present and target-absent slopes, respectively). Correspondingly, the confidence interval for the mean ratio would be widened (-12.57 to 49.89 ms/item).

for 99.5% of the variance in the interaction. Other effects reflect trends across sessions (see Appendix B).

The pattern of slopes across sessions indicates that search processes can become automatized in the sense suggested by Schneider and Shiffrin (1977). However, unlike findings suggesting parallel search for both target-present and target-absent trials (e.g., Donnelly et al., 1991; Enns & Rensink, 1991a; Treisman & Sato, 1990), target-absent slopes in the present experiment do not approach similar values. As the relatively large slope ratios of Table 10 indicate, the flattening of target-present slopes is not paralleled by a flattening of target-absent slopes. Treisman and Souther (1985) have also reported conditions under which the presence of a target is detected in parallel but its absence needs to be confirmed by serial search. The most probable explanation is that participants scan target-absent displays to confirm that the target has not been missed (Egeth et al., 1984). Treisman and Souther argued that the mere presence of a target is sufficient to trigger activity in the feature maps and enables responses based on preattentive processing. The absence of target information does not change the activity in the feature maps and thus requires serial processing.

Error rates. Error rates (see Table 11) are characterized by main effects of target presence ($F(1, 7) = 36.48$, $MS_e = 83.1$, $p < .001$), of vertex type ($F(1, 7) = 37.02$, $MS_e = 14.5$, $p < .001$), and of display size ($F(2, 14) = 21.25$, $MS_e = 23.9$, $p < .001$). Target presence interacts with vertex type ($F(1, 7) = 39.98$, $MS_e = 13.9$, $p < .001$) and with display size ($F(2, 14) = 15.13$, $MS_e = 25.9$, $p < .02$) to influence error rates. As with Experiment 3, error rates are consistent with the notion that a response criterion is set such that not all items in a display are included in the attentional window and or resolution is decreased with wider breadth of attention. This leads to a greater proportion of errors on target-present trials than on target-absent trials (Cave & Wolfe, 1990).

EXPERIMENT 6

The results of Experiment 5 suggest that 3D object descriptions are processed in parallel, as indicated by the time to detect a misaligned vertex. However, an examination of individual subject slopes (see Table 9) suggests that 3D object descriptions are not inherently computed in parallel from vertices alone for all participants; some practice with the task and stimuli is required to develop automatic processes. Learning can be very rapid for some participants, but for others the need to practice to achieve rapid search suggests a change in the processes involved. The need for practice for some participants to achieve

Table 11

Error Rates (in percentages) across Vertex Types and Sessions of Experiment 5.

	Target present			Target absent		
	Display size			Display size		
	2	6	12	2	6	12
2-line vertex						
Session 1	2.34	3.91	8.07	0.78	2.61	1.04
Session 2	2.34	2.34	9.90	0.78	1.04	2.08
Session 3	1.56	3.12	8.07	1.30	1.82	0.52
Session 4	1.82	3.65	7.29	1.30	1.04	1.56
3-line vertex						
Session 1	6.77	10.16	16.67	1.04	1.30	1.56
Session 2	5.99	5.73	12.50	0.52	2.08	1.30
Session 3	5.21	6.51	12.76	1.04	1.04	2.08
Session 4	7.03	8.33	14.06	0.52	0.78	2.08

relatively flat search functions suggests a change in the processes involved, consistent with the notion of a continuum of processing.

An alternative account is that participants require some time to recognize that the external vertices of 3D contours (i.e., simpler 2D contours) are sufficient to perform the task. Thus, the purpose of the present experiment is to determine whether vertex-only 2D contours are processed in parallel in the context of multiple-object displays. The stimuli for the present experiment are those used in Experiment 5, modified by removing the trihedral vertex in the center of an object's configuration as well as the central line segment of trihedral vertices along the contour (see Figure 15). This modification reduces contours to 2D shapes that are comparable, in most respects, to Donnelly et al.'s (1991) stimuli.

The main hypothesis of the present experiment is that 2D contours will be sufficient to derive object descriptions in parallel across more than one object, and that this is what led to the relatively rapid search found in Experiment 5. Support for this hypothesis with multiple objects will extend Donnelly et al.'s finding that vertices of single 2D objects are processed in parallel. Data supporting the hypothesis will also provide a potential explanation for the results of Experiment 5. In particular, the results of Experiment 5 would be attributable to an artifact of the presence of a 2D closed contour in the depicted 3D objects. In contrast, if 2D contours are insufficient to account for the parallel detection of inconsistent vertices in multiple-object displays (i.e., indicated by sloped search functions), then 3D object descriptions must have been involved in Experiment 5. The absence of parallel detection would imply that the nature of the stimulus (2D or 3D contours) contributes to the efficiency of search process, suggesting that perceptual grouping of vertices depicting 2D and 3D contours occur differently.

Method

Stimuli and Design. Vertex-only contours of Experiment 5 are modified by deleting all internal edges from depicted 3D blocks used in Experiment 5 (see Figure 15). As a result, the remaining vertices cannot be interpreted as 3D blocks, but are in fact more readily interpretable as hexagons at 45° in the picture plane. Beyond this manipulation, the design is modified to include single-object displays to ensure compatibility of the results with those of Donnelly et al. (1991).

The experimental design is a 2 (Target Presence: Present or Absent) X 4 (Display Size: 1, 2, 6, or 12 items) X 4 (Sessions) within-subject design. All displays consist of randomly-arranged displays. Each experimental condition is represented by 18 trials

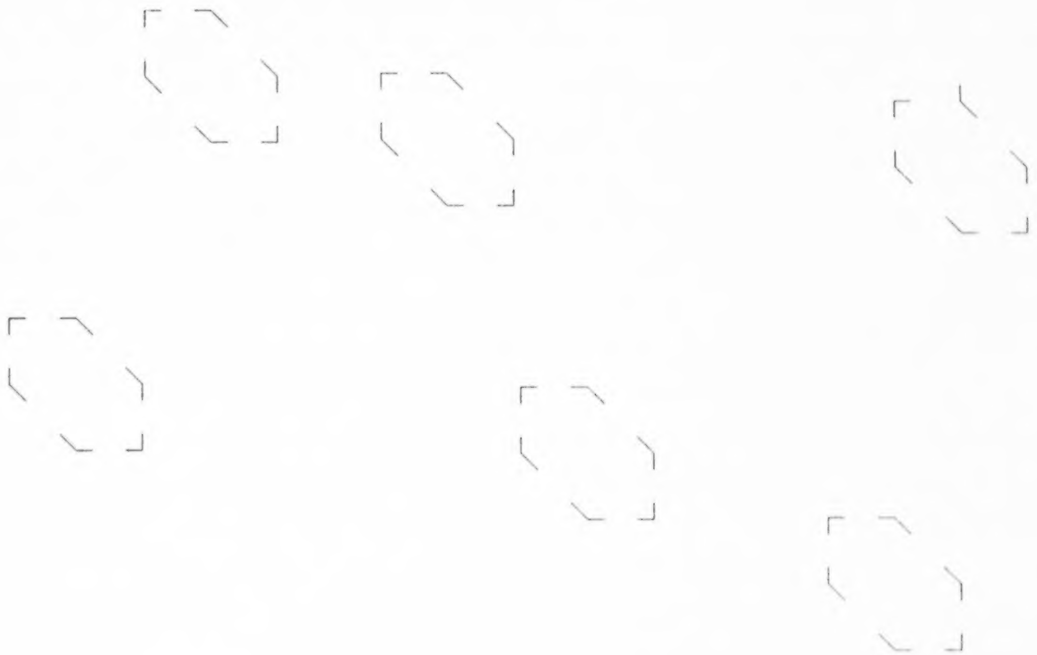


Figure 15. Example of a vertex-only 2D-contour stimulus used in Experiment 6. The misaligned vertex is located at the top of the top-right object.

throughout the trial sequence. In all other respects, the stimuli and design are the same as in Experiment 5.

Procedure. The procedure is identical to that of Experiment 5.

Subjects. The nine participants (4 females) had participated in only one previous experiment of this research program (excluding Experiment 5). One male participant committed a high percentage of errors on target-present, 12-item displays (30.90%) across sessions (ranging from 20.83% to 41.67%) and his data are excluded from further analyses.

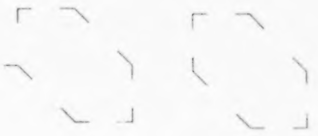
Results and Discussion

Mean correct RTs are plotted as a function of display size in Figure 16 and individual subject slopes are reported in Table 12. Note that 1-object displays are not included in the analysis of slopes, to ensure comparability of slopes with previous experimental results. However, mean RTs for 1- and 2-object displays are contrasted for comparison with Donnelly et al.'s (1991, Experiment 4) results. The comparison will be presented after the main analysis of slopes.

The results of this experiment are interesting when compared to those of Experiment 5. Arguments that 2D object descriptions are responsible for the effects observed in Experiment 5 are not supported. In fact, there is no evidence of parallel recovery of 2D object descriptions in any of the sessions. Donnelly et al.'s (1991) findings that 2D object descriptions are available preattentively from vertices only is apparently restricted to single-object displays. These observations are supported by the following statistical analyses.

Slopes. As expected, slopes (see Table 13) are reliably different across target-present and target-absent trials ($F(1, 7) = 33.43$, $MS_e = 720$, $p < .001$), with target-present trials resulting in a shallower slope than target-absent trials (29 vs. 67 ms/item, respectively). The effect of session on slopes is also reliable ($F(3, 21) = 18.98$, $MS_e = 97.7$, $p < .001$). In addition, the interaction of target presence and session ($F(3,21) = 4.11$, $MS_e = 75.2$, $p < .05$) reveals a sharper decrease in slopes across sessions for target-absent trials than for target-present trials (36 ms/item compared to 15 ms/item, respectively).

As indicated in Table 13, the confidence intervals for slope ratios in every session encompass the 2:1 ratio expected for serial processing, even though slopes decrease across sessions. These results favor the suggestion that 2D surface descriptions are not responsible for the parallel detection of misaligned vertices obtained in Experiment 5 with 3D object contours. The search rates observed in Experiment 6 can be compared to the search rates in Experiment 5 where 2-line vertices are searched. In the previous experiment, search for 2-line vertices did not differ from search for 3-line vertices. In both cases, search



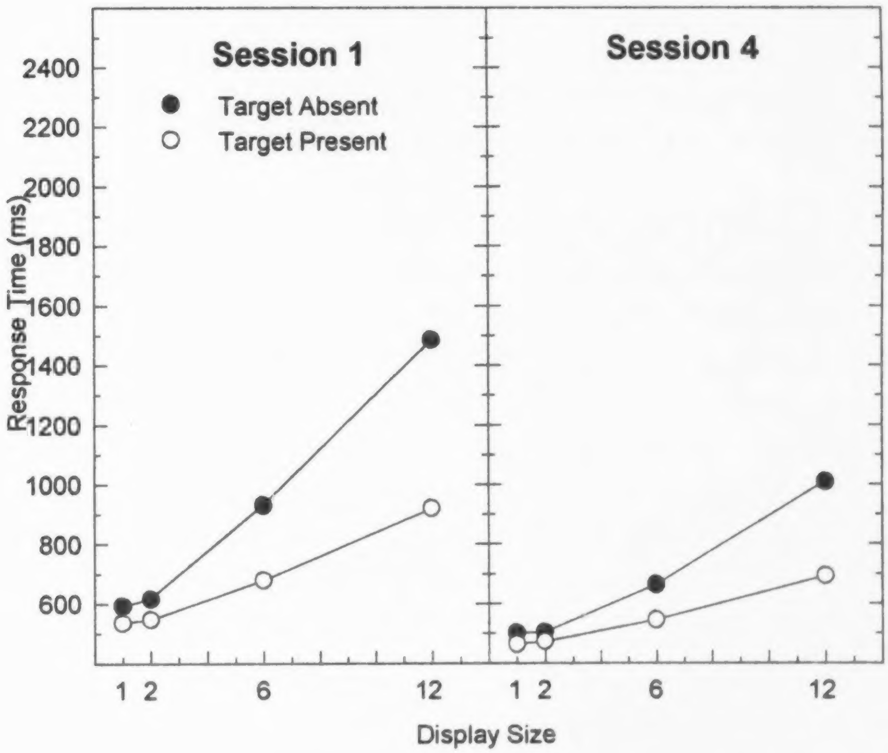


Figure 16. Search functions for a misaligned vertex with 2D contours in the first and last sessions of Experiment 6 (CL = ± 7.99 ms).

Table 12

Individual Search Slopes (in ms/item) for Target-Present and Target-Absent Trials by Session of Experiment 6.

	Target present				Target absent			
	Session				Session			
	1	2	3	4	1	2	3	4
Subject 1	31.2	24.6	22.8	23.5	50.9	45.2	38.2	27.2
Subject 2	33.0	18.3	19.4	12.4	71.7	54.8	60.3	41.4
Subject 3	34.0	25.0	21.3	21.2	85.4	67.5	58.1	52.9
Subject 4	42.6	36.5	44.1	33.7	106.7	66.8	86.5	50.6
Subject 5	36.0	37.6	32.2	30.7	90.8	80.2	81.8	74.1
Subject 6	30.5	19.4	13.4	7.3	62.3	34.1	25.7	20.2
Subject 7	43.5	28.6	36.6	25.6	157.5	107.9	96.4	78.5
Subject 8	49.4	35.6	24.5	23.4	73.0	94.5	54.0	63.7
Mean	37.5	28.2	26.8	22.2	87.3	68.9	62.6	51.1
Std dev.	6.4	7.2	9.4	8.2	31.1	23.1	22.8	19.6

Note. Slopes are computed across 2- through 12-object trials.

Table 13

Search Slopes (in ms/item) across Sessions of Experiment 6.

	Target present	CI (95%)	Target absent	CI (95%)	Ratio	CI (95%)
Session 1	37.5	32.2 to 42.9	87.3	61.4 to 113.2	2.31	1.79 to 2.83
Session 2	28.2	22.2 to 34.1	68.9	49.6 to 88.2	2.46	1.91 to 3.01
Session 3	26.8	18.9 to 34.7	62.6	43.7 to 81.6	2.35	1.97 to 2.72
Session 4	22.2	15.4 to 29.1	51.1	34.8 to 67.4	2.43	1.85 to 3.02

Note. Slopes are computed across 2- through 12-object trials.

slopes, as well as search ratios, were equivalent for 2-line and 3-line vertices. Search slopes for target-absent trials did not differ across both experiments (64.3 and 67.5 ms/item for Experiments 5 and 6, respectively), but the slope for target-present trials is steeper in Experiment 6 than in Experiment 5 (28.7 vs. 15.7 ms/item, respectively). The relatively large slope ratios of Experiment 5 compared to those of the present experiment attest to this comparison. The contrast between the two experiments suggest that the context provided by 3D contours facilitates the processing of vertices (cf. McClelland & Miller, 1979; Pomerantz et al., 1977; Weisstein & Harris, 1974).

All of the RT functions are largely described by linear components, or interactions with linear components, of display size. The linear component of display size ($F(1, 7) = 83.88$, $MS_e = 86636$, $p < .001$) accounts for 96.4% of the variance. The linear component interacts with target presence and accounts for a 96.1% ($F(1, 7) = 33.95$, $MS_e = 34795$, $p < .001$) of the variance in the interaction. The remaining variance is reliably accounted for by a quadratic function for display size ($F(1, 7) = 34.59$, $MS_e = 7826$, $p < .001$) and for target presence by display size ($F(1, 7) = 11.02$, $MS_e = 4339$, $p < .02$). The polynomial trends involving session are reported in Appendix B.

The comparison of mean RTs for 1- and 2-object displays indicates that these means are not different from one another ($LSD(1, 42) < 63.77$, $p < .01$). Mean RTs for 1-object displays across sessions were 488 ms and 536 ms for target-present and target-absent trials, respectively. The corresponding mean RTs for 2-object displays were 501 ms and 540 ms. This comparison is notable when compared to a similar comparison carried out by Donnelly et al. (1991, Experiment 4). In their study, the effect of dual configurations was to increase RTs, compared to single-configuration displays (an overall increase of 77 ms and 36 ms for target-absent and target-present trials, respectively). Donnelly et al. concluded that access to object descriptions is limited to one object at a time. In contrast to the random location of single-object displays in the present experiment, those used by Donnelly et al. were centered at fixation. In addition, double-configurations in Donnelly et al. were equidistant from fixation, whereas those of the present study were randomly arranged.

These differences provide a clue to the comparable RTs observed in the present experiment. Humphreys, Riddoch, and Müller (cited in Donnelly et al., 1991) suggested that the window of attention is fitted to a single object. A fixed location, as in Donnelly et al., might serve as a cue to direct attention before the onset of a trial. In contrast, randomly-arranged displays eliminate this cue, thus requiring that the attentional system search for an object.

Error rates. The usual finding that more errors are committed with larger target-present displays (see Table 14) than with comparable target-absent displays is supported. Target presence ($F(1, 7) = 61.47$, $MS_e = 19.4$, $p < .001$) and display size ($F(3, 21) = 28.37$, $MS_e = 16.4$, $p < .001$) reliably determine error rates, as does their interaction ($F(3, 21) = 23.56$, $MS_e = 11.2$, $p < .001$).

EXPERIMENT 7

The stimuli of Experiments 5 and 6 do not permit a direct comparison of their results, because 2D contours contain fewer line segments than do 3D contours. Thus, the present experiment is designed to control for the comparison of performance with 2D and 3D contours. In addition to stimuli used in Experiments 5 and 6, a control stimulus is included in the present design (see Figure 17). These stimuli, referred to as quasi-3D contours, are included to prevent the possible interpretation that the internal line segments of 3D vertex-only contours enable easy grouping of vertices in Experiment 5. The control stimuli are comparable to the 3D contours, but do not readily exhibit a 3D structure.

The main hypothesis of this experiment is that object descriptions will be recovered in parallel only from vertex-only contours of 3D objects, as found in Experiment 5. In contrast, vertex-only contours of 2D objects and modified vertex-only 3D contours, matched to 3D contours for the number of line segments, are not expected to yield parallel recovery of object descriptions. Relative differences across contour types will suggest systematic differences as a function of possible interpretations of object contours.

Such a pattern of results will support the conclusion that 3D information can be recovered in parallel from vertices only in multiple-object displays. Furthermore, it will be possible to conclude that this property of 3D contours is not shared with 2D contours. However, should quasi-3D contours yield search functions similar to search functions for 3D contours, then interpretations will rest on the notion that internal vertices facilitate the grouping of vertices. That is, the extension of internal vertices toward a common area might suggest a perceptual grouping, even though the line segments would not intersect at a common point.

Method

Stimuli and Design. The stimuli consist of one of three types of vertex-only contours. Contour type is a between-subjects factor to allow comparison with results of Experiments 5 and 6, and because Experiments 1 and 2 confirmed that blocked presentation is

Table 14

Error Rates (in percentages) across Sessions of Experiment 6.

	Target present				Target absent			
	Display size				Display size			
	1	2	6	12	1	2	6	12
Session 1	1.22	1.91	6.77	13.37	1.22	1.04	0.52	1.56
Session 2	2.09	3.13	5.38	13.54	2.09	0.52	0.87	1.74
Session 3	0.87	2.60	6.25	11.11	1.56	0.35	0.52	4.69
Session 4	3.47	3.99	4.86	11.11	1.91	0.17	1.22	2.61

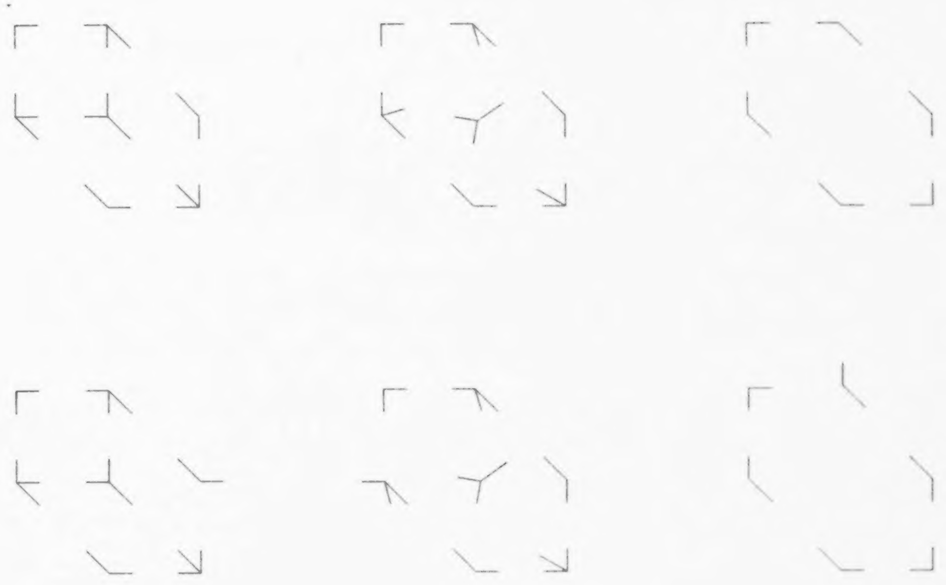


Figure 17. Example of nontarget (top row) and target (bottom row) objects for 3D, modified-3D, and 2D contours used as stimuli in Experiment 7. A target-present trial contains one of the objects on the bottom row and the remaining objects in a trial consist of the object immediately above the target in question. This figure is not an actual stimulus.

necessary to observe the improvement in performance across sessions. A target object and a nontarget object for each stimulus type are shown in Figure 17. The first stimulus type corresponds to the vertex-only 3D contours used in Experiment 5 (see the left column of Figure 17). The second stimulus type is created by modifying the vertex-only 3D contours of Experiment 5 (see the middle column of Figure 17). The modification consists of rotating the internal trihedral vertex and tilting the central line segment of external vertices. In this way, the number of line segments is the same as with 3D contours, but the depicted structure is no longer 3D. Finally, the third stimulus type corresponds to the vertex-only 2D contours used in Experiment 6 (see the right column of Figure 17). As with Experiment 6, there are 1-, 2-, 6-, and 12-object displays for each contour-type condition.

The design is a 2 (Target Presence: Present or Absent) X 4 (Display Size: 1, 2, 6, or 12 items) X 4 (Sessions) X 3 (Contour Type: 2D, 3D, or quasi-3D) mixed design, with the last factor as a between-subjects factors. As with Experiments 5 and 6, vertex type and vertex location are crossed and equally represented within each experimental condition for a given contour type. Across the four sessions, there is a possibility of 72 correct responses per experimental cell.

Procedure. The procedure is identical to that of Experiments 5 and 6.

Subjects. Eight participants (4 females) were recruited for each of three contour-type conditions. Participants had previously participated in only one of the first four visual-search experiments reported in this study.

Results and Discussion

Mean correct RTs are plotted in Figure 18 as a function of display size for the first and the last sessions for each contour type. Individual subject slopes are reported in Table 15. One-object displays are treated in the same way as they are in Experiment 6. The most critical result of this experiment is the failure to replicate the results of Experiment 5 for the 3D contours. The parallel recovery of misaligned vertices is not obtained with 3D contours, as it was in Experiment 5. However, and regardless of contour type, search becomes more efficient with repeated practice on the task, while remaining within a 2:1 ratio, which suggests that search operates along a continuum of processing.

Slopes. The results of Experiment 5 and 6 are only partially replicated. The main effect of contour type ($F(2, 21) = 4.67$, $MS_e = 2917$, $p < .02$), seen in Figure 18, shows that 2D contours gives rise to the shallowest slopes (40 ms/item averaged across sessions and target presence) and 3D contours yield the steepest slopes (67 ms/item). The average slope for quasi-3D contours is comparable to that of 3D contours (64 ms/item). As predicted,

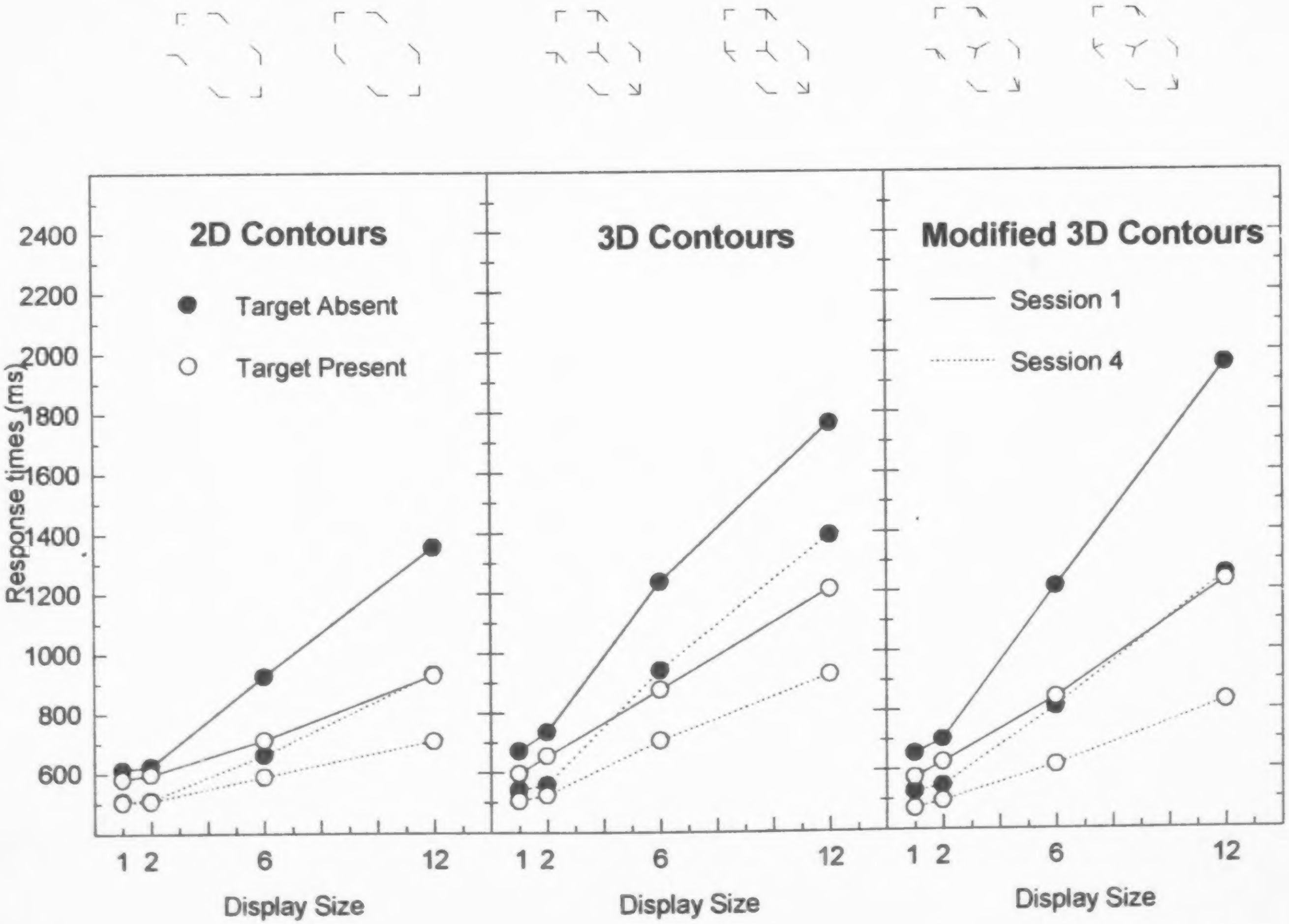


Figure 18. Search functions for a misaligned vertex with 2D, 3D, and modified-3D contours (blocked between-subjects presentation) in the first and last sessions of Experiment 7 (CL = ± 7.84 ms).

Table 15

Individual Search Slopes (in ms/item) for Target-Present and Target-Absent Trials by Session of Experiment 7.

	Target present				Target absent			
	Session				Session			
	1	2	3	4	1	2	3	4
2D contours								
Subject 1	25.2	29.7	17.8	14.8	36.8	74.3	45.1	33.9
Subject 2	17.8	20.0	12.3	14.1	41.1	30.4	29.4	31.9
Subject 3	51.0	20.7	22.4	20.8	90.9	53.2	51.2	45.1
Subject 4	39.7	29.3	32.1	23.3	128.8	108.2	112.6	68.4
Subject 5	38.0	19.8	12.5	14.9	80.3	31.8	14.7	11.2
Subject 6	29.2	17.7	10.8	17.3	78.3	34.8	27.5	31.8
Subject 7	31.2	29.1	26.7	33.5	69.2	60.5	63.9	71.3
Subject 8	35.2	44.2	28.6	21.4	60.8	79.3	63.0	45.6
Mean	33.4	26.3	20.4	20.0	73.2	59.1	50.9	42.4
Std dev.	9.4	8.2	7.7	6.0	27.4	25.6	28.5	18.7

Table 15 (continued)

	Target present				Target absent			
	Session				Session			
	1	2	3	4	1	2	3	4
3D contours								
Subject 1	53.6	37.6	42.3	41.1	83.0	97.4	75.9	98.8
Subject 2	63.2	47.7	42.8	27.3	109.5	94.8	81.5	68.4
Subject 3	59.4	55.1	42.2	54.5	126.2	90.5	85.8	89.9
Subject 4	63.3	41.6	36.5	47.9	93.1	98.8	80.8	122.9
Subject 5	46.8	40.0	38.6	27.1	98.9	90.2	70.9	55.5
Subject 6	47.2	41.2	30.9	36.2	92.2	82.2	66.8	61.9
Subject 7	34.6	48.5	34.7	37.5	55.2	66.0	88.1	73.3
Subject 8	75.4	68.5	37.1	46.2	154.0	128.3	97.4	90.2
Mean	55.4	47.5	38.1	39.7	101.5	93.5	80.9	82.6
Std dev.	11.8	9.5	3.9	9.1	27.6	16.4	9.2	20.8

Table 15 (continued)

	Target present				Target absent			
	Session				Session			
	1	2	3	4	1	2	3	4
Modified-3D contours								
Subject 1	26.6	28.1	15.2	13.8	68.0	50.4	29.8	23.4
Subject 2	56.9	50.5	49.1	38.8	141.2	99.3	84.9	68.3
Subject 3	46.9	23.4	24.3	21.6	89.8	40.3	31.6	46.6
Subject 4	64.5	47.9	40.5	26.9	112.2	70.0	76.3	66.6
Subject 5	110.8	64.0	52.5	58.9	193.9	138.8	133.5	141.4
Subject 6	42.8	15.9	11.4	13.3	115.5	28.8	13.7	24.4
Subject 7	61.2	46.8	49.2	51.9	142.6	108.9	91.0	115.1
Subject 8	79.4	46.3	33.3	42.6	140.2	105.4	83.8	81.1
Mean	61.1	40.4	34.4	33.5	125.4	80.2	68.1	70.9
Std dev.	23.9	15.1	15.0	16.1	35.9	36.2	37.3	38.8

Note. Slopes are computed across 2- through 12-object trials.

the reduction in search rates across sessions (see Table 16) indicates that search rates are sensitive to practice on the task (*F*(3, 63) = 35.98, MS_e = 209, $p < .001$). The interaction of contour type with session (*F*(6, 63) = 3.53, MS_e = 209, $p < .02$) shows a greater reduction in search rates across sessions for quasi-3D contours than for 2D or 3D contours. As expected, the main effect of target presence (*F*(1, 21) = 132.26, MS_e = 577, $p < .001$) is supported.

A problem with the data is the fact that 3D contours do not yield relatively flat search functions, as in Experiment 5. Although differences between individuals can occur either as a function of the time needed to develop efficient processing or in the capability of developing such processes, no obvious patterns are suggested by the individual slope data in Table 15. A possible explanation for the difference in search patterns between Experiments 5 and 7 will be provided in the discussion of Experiments 5 through 7.

As can be seen in Table 16, the ratio of slopes for all conditions approximate the 2:1 ratio attributed to serial processing. Thus, the pattern of slopes can be interpreted to mean that all displays are searched serially, as suggested by feature-integration theory. In addition, the reduction in slopes suggests that search can become relatively more efficient while still depending generally on serial operations. For all effects obtained, linear functions account for more than 95% of the variance. This is the case for the main effect of display size (*F*(1, 21) = 221.36, MS_e = 143654, $p < .001$; 98.96% of the variance) and for its interaction with target presence (*F*(1, 21) = 136.51, MS_e = 28266, $p < .001$; 99.57%). In addition, contour type (the between-subject factor) interacts with the linear function of display size (*F*(2, 21) = 4.90, MS_e = 143654, $p < .02$; 96.34%). The remaining variance for these effects (less than 5%) is accounted for by reliable quadratic components. Other trends reflecting changes across sessions are tabled in Appendix B.

As with mean RTs of Experiment 6, the comparison of 1- and 2-object displays shows that these two display sizes are not processed differently (*LSD*(1, 126) < 51.95, $p < .05$). This is the case for all sessions. Mean RTs for target-present and target-absent trials are 525 ms and 568 ms for 1-object trials and 553 ms and 591 ms for 2-object trials. The only exception is for 3D contours in Session 1 (672 vs. 737 ms for 1- and 2-object trials, respectively; *LSD*(1, 126) = 64.62 for target-absent displays, and 596 vs. 655 ms for 1- and 2-object trials, respectively; *LSD*(1, 126) = 58.50 for target-present displays). Again, this pattern is contrary to the one reported by Donnelly et al. (1991) when comparing performance

Table 16

Search Slopes (in ms/item) across Contour Types and Sessions of Experiment 7.

	Target present	CI (95%)	Target absent	CI (95%)	Ratio	CI (95%)
2D contours						
Session 1	33.4	25.6 to 41.3	73.2	50.4 to 96.1	2.19	1.75 to 2.64
Session 2	26.3	19.5 to 33.1	59.1	37.7 to 80.4	2.22	1.66 to 2.77
Session 3	20.4	14.0 to 26.8	50.9	27.2 to 74.7	2.38	1.88 to 2.87
Session 4	20.0	15.0 to 25.0	42.4	26.8 to 58.0	2.06	1.58 to 2.54
3D contours						
Session 1	55.4	45.6 to 65.3	101.5	78.5 to 124.5	1.82	1.61 to 2.03
Session 2	47.5	39.6 to 55.5	93.5	79.8 to 107.2	2.01	1.70 to 2.32
Session 3	38.1	34.9 to 41.4	80.9	73.3 to 88.6	2.14	1.90 to 2.38
Session 4	39.7	32.2 to 47.3	82.6	65.3 to 99.9	2.10	1.82 to 2.37
Modified 3D contours						
Session 1	61.1	41.2 to 81.1	125.4	95.5 to 155.4	2.15	1.84 to 2.47
Session 2	40.4	27.7 to 53.0	80.2	50.0 to 110.4	1.94	1.71 to 2.18
Session 3	34.4	21.9 to 47.0	68.1	36.9 to 99.2	1.87	1.49 to 2.25
Session 4	33.5	20.0 to 46.9	70.9	38.5 to 103.3	2.06	1.82 to 2.29

Note. Slopes are computed across 2- through 12-object trials.

on single- and double-configuration displays. The conjecture that fixed-location displays in Donnelly et al. acted as a facilitating cue still holds.

Error rates. The error data parallel the patterns observed in previous experiments (see Table 17). More errors are committed with target-present trials than with target-absent trials. This effect is attenuated with vertex-only 2D contours compared to vertex-only 3D and quasi-3D contours. There is a reliable effect of target presence ($F(1, 21) = 222.68$, $MS_e = 68$, $p < .001$) and of contour type ($F(2, 21) = 4.72$, $MS_e = 77$, $p < .02$) on accuracy. The interaction of these two factors confirms both main effects ($F(2, 21) = 5.89$, $MSe = 69$, $p < .009$). As expected, the effect of display size ($F(3, 63) = 176.22$, $MS_e = 33$, $p < .001$) is qualified by its interaction with target presence ($F(3, 63) = 150.31$, $MS_e = 29$, $p < .001$). There are no other effects influencing error rates.

DISCUSSION OF EXPERIMENTS 5 THROUGH 7

From Experiment 5, there was encouraging evidence that a misaligned vertex can be detected very rapidly, and perhaps, in parallel across multiple objects, when it is embedded in a vertex-only 3D contour. This evidence is consistent with the finding that the perception of a visual target is known to depend on the context in which it is embedded (McClelland & Miller, 1979; Pomerantz et al., 1977; Weisstein & Harris, 1974). A preliminary conclusion, based on a comparison of results from Experiments 5 and 6, suggested that the three-dimensionality of the context was necessary for the parallel detection of misaligned vertices. Indeed, the configuration of vertices into 2D contours (as in Experiment 6) did not produce evidence of parallel processing of vertices. However, claims that parallel processing is restricted to 3D contours are unsupported in Experiment 7. The results of Experiment 7 indicate that object descriptions, whether 2D or 3D, computed on the basis of vertices alone are not inherently accessed in parallel in multiple-object displays, although serial search can become very rapid (i.e., relatively shallow search functions). The results of Experiment 5 are not necessarily incompatible with those of Experiments 6 and 7. A general account of the results of Experiments 6 and 7 is presented, and the results of Experiment 5 are then discussed in the context of this account. The proposed explanation is then revised to account for the results of Experiments 1 through 4.

It was suggested earlier that variations in search slopes indicate quantitative differences along a continuum of processing. Conversely, a qualitative difference might suggest that different processes are used for visual search. Inferences regarding qualitative differences in the present thesis are based on differences in slope ratios between conditions.

Table 17

Error Rates (in percentages) across Contour Types and Sessions of Experiment 7.

	Target present				Target absent			
	Display size				Display size			
	1	2	6	12	1	2	6	12
2D contours								
Session 1	2.43	3.65	6.42	20.31	3.82	0.87	1.39	2.95
Session 2	2.78	2.95	9.20	21.35	2.09	1.74	0.87	1.91
Session 3	2.61	2.61	10.07	23.26	2.26	0.70	2.09	4.86
Session 4	1.91	4.17	10.25	20.66	2.43	2.09	2.08	5.38
3D contours								
Session 1	2.43	5.56	15.63	32.81	2.78	1.04	2.61	3.30
Session 2	2.61	7.29	15.62	28.12	2.26	0.70	1.22	2.95
Session 3	2.78	6.43	15.45	31.77	2.43	0.87	1.91	3.65
Session 4	2.95	7.81	14.06	29.86	2.43	0.87	2.26	4.34
Modified-3D contours								
Session 1	0.87	5.04	10.24	19.27	1.56	0.52	1.74	1.91
Session 2	1.74	6.08	12.15	24.31	2.78	0.52	2.08	3.82
Session 3	3.13	5.04	9.90	26.57	3.30	1.22	2.61	4.34
Session 4	2.26	4.34	12.33	26.39	2.08	1.91	2.95	3.30

As such, the pattern of results from Experiments 5 through 7 corroborate the notion of a continuum of processing. Slopes vary from very slow to very fast, although slope ratios generally remain within the 2:1 range suggested by self-terminating serial search. Target-present and target-absent search slopes in every condition of Experiments 6 and 7 yield a 2:1 slope ratio. Therefore, the results of these experiments are most simply interpreted to mean that search across multiple objects is attributable to serial processes. Furthermore, even with practice on the task, which leads to relatively flat search functions for some target-present conditions, the slope ratios between target-absent and target-present search functions remain within a 2:1 range. A decrease in the amount of time required to process a display of objects (i.e., a quantitative difference) does not in itself qualify as evidence of parallel processing. In contrast, a qualitative difference in processing, indicated by the relation between target-present and target-absent search functions, would support the distinction between serial and preattentive processing. Thus, if a different pattern had been observed across sessions, parallel processing might have been inferred. For example, if slope ratios reliably different from the 2:1 ratio had been obtained, then the qualitative difference (whether across sessions or between conditions) could have been attributed to the influence of parallel processes. Thus, although practice on the task was expected to result in evidence of parallel processing, the pattern of performance across sessions does not generally corroborate such a view. Rather, these results are consistent with the notion of a continuum of processing, ranging from very slow to very fast search rates. The shallower search functions observed for 2D contours compared to 3D and quasi-3D contours corroborates the argument that relatively simple stimuli lead to relatively easy search.

The use of serial processing to search multiple-object displays in Experiments 6 and 7 is compatible with the findings and interpretation of Donnelly et al. (1991). Recall that these authors concluded that a collection of vertices comprising a single object can be processed in parallel to recover an object description of the represented object. The parallel processing of vertices for a single object is still viable to account for the search performance observed in the present research. However, the processing of multiple objects in a display is limited to a serial scan across objects. In summary, the processing of information belonging to a single object is likely to be carried out in parallel, as was concluded by Donnelly et al. (1991), but each object in the display becomes the focus of processing in a serial fashion. Although possible, such an account is somewhat misleading: The breadth of attention may not be restricted to a single object (Humphreys et al., cited in Donnelly et al., 1991). This conclusion is supported by comparison of search times with 1- and 2-object displays in Experiments 6 and 7. Response times with these displays do not differ from one another, suggesting that more than one object can be included in a single attentional scan.

The idea that more than one object can be encapsulated in the window of attention on a given search scan suggests a possible mechanism to account for the improvement in search across sessions. In addition, as will be seen presently, the same account can accommodate the results of Experiment 5. It was conjectured earlier that observers could develop more efficient ways of processing multiple-object displays with sufficient practice on the task. Display parameters (e.g. object alignment) and task parameters (e.g., blocked presentation) were also conducive to developing such efficiencies. The difference in search patterns across sessions was expected to reflect a change toward the adoption of parallel-processing strategies. Recall that for slopes to be considered as evidence of parallel processing, the slope ratio would have had to be reliably different than 2:1. Although the pattern of results for Experiments 6 and 7 does not explicitly support the hypothesis that parallel processes develop with practice, the reduction in slopes across sessions indicates that participants became more efficient in their search. If improvement in search time was solely a function of more rapid serial search, then slopes would remain the same even though overall response times would decrease.

One way in which search can be improved, yet still reflect a serial search strategy, is for observers to search a group of objects with each attentional scan (cf. Pashler, 1987). This search strategy could initially be a function of display size, with relatively larger displays eliciting the grouping of objects more readily than would relatively smaller displays. The overall time to scan a 12-object display, for example, could be reduced by half if two objects were included in each scan. In this way, display size is functionally reduced, but groups of objects must still be scanned separately to respond. Fewer scans would account for the reduced slopes observed in later sessions. Eventually, if observers could develop a grouping strategy that encompassed the entire display, independent of display size, then search functions could reflect evidence of parallel processing.

Another possibility is for observers to construct search templates consistent with the stimuli being searched. This notion is compatible with the template notion advanced by Treisman (1993). Template-matching as a selective mechanism, however, has been proposed only as an inhibitory mechanism, filtering out irrelevant information (but see Cave & Wolfe, 1990; Duncan & Humphreys, 1989). For Treisman (1993), an inhibitory template is used to reject nontargets: A template is set up to match a randomly selected object in the display and is then used to suppress all matching objects.

In the present argument, the search template is more akin to Duncan and Humphreys' (1989) notion of template than to Treisman's (1993) notion of template. To account for the effect of practice on 3D-orientation detection, the template is used to identify discriminating features of the target, such as the central y-vertex. For the first four experiments, the y-vertex is rotated 180° in the target object compared to nontarget objects. For the later experiments involving inconsistent vertices, a single template might identify a set of vertices likely to distinguish the target. In this case, the presence of any such combination of vertices would yield a match. The results of Experiments 5 through 7 indicate that a template is not established a priori, otherwise search performance would not change across sessions in the way reflected by the slopes. The characteristic of the present data not addressed by feature-integration theory or other models of visual attention is the change in slopes across sessions. The present data cannot distinguish between an automatization of processes or a modification of a search template. However, these notions are not mutually exclusive and, unless data are produced to distinguish between them, both remain viable within an integrated account of visual search.

Assuming either of these accounts is appropriate to describe the observed results, then the results of Experiment 5 have a probable explanation. In this experiment, search functions were relatively shallow, and unlike Experiments 6 and 7, the slope ratios were reliably greater than a 2:1 ratio. Such slope ratios, in conjunction with relatively shallow slopes, suggest that target-present trials were processed in parallel. In contrast, steeper slopes for target-absent trials suggest the use of serial processes, possibly to confirm the absence of a target (cf. Egeth et al., 1972).

In retrospect, the difference between the results of Experiment 5 and the other two experiments -- especially in comparison to identical 3D contours in Experiment 7 -- is probably the result of subject-selection procedure. Participants in both experiments had taken part in only one previous experiment and were recruited from the same population. Nevertheless, due to the time between experiments, participants in Experiment 5 had more recently participated in a previous experiment than had participants in Experiments 6 and 7. The recency of their experience might have allowed residual effects of participation to carry over to Experiment 5. As such, participants in Experiment 5 might have been able to perform the task more expediently than participants in other experiments. Such an affinity with the task was no longer available to participants in Experiments 6 and 7. The pattern of results in Experiment 5 does not contradict the general interpretation provided earlier. Although the overall evidence is insufficient to support claims that processing can occur in parallel, the results of Experiment 5 suggest that some conditions can lead to parallel processing. Further research is needed to confirm this hypothesis.

Parenthetically, if target-absent slopes had been relatively flat and slope ratios had been smaller than 2:1, then this pattern would have suggested that both target-present and target-absent trials had been processed in parallel. Thus, search functions for target-present trials in Experiment 5 might be attributable to the grouping of objects in the display as described in the previous paragraph. This account, however, remains speculative because target-absent trials did not yield flat slopes similar to target-present trials. In future research, experimental conditions could be set out to prevent observers from scanning the display before giving their responses. For example, if displays were presented for very brief durations, and maybe masked, then observers could not rely on a confirmation strategy with target-absent trials.

Enns and Rensink's (1991a) argued that the "collection of junctions in an item must be connected by lines if they are to be detected rapidly (p. 341)". Enns (1992) proposed that local estimates of 3D orientation are obtained in parallel from information available in vertices. More precisely, the 3D orientation of abutting surfaces that generate a vertex can be estimated from the arrangement of lines at that vertex (also see Binford, 1981; Hummel & Biederman, 1992; Waltz, 1975). According to Enns, this operation would be carried out locally, but in parallel across all vertices of an object and across all objects in a display when complete contours are represented in line drawings. As a result, if estimates of 3D orientation are consistent across vertices, then the focus of the visual system is directed to other areas of the figure to complete the structural specification of the figure.

The pattern of results in Experiment 5 suggest that under some conditions the visual system is capable of connecting virtual lines in parallel from vertex-only contours, or alternatively, of deriving an object description in parallel from vertices alone in multiple-object displays. Although similar results were not observed in Experiments 6 and 7, observers did reduce the time needed to scan from one object to another in a display, yet multiple-object displays still needed to be scanned serially. According to Enns (1992), a single misaligned vertex in target-present displays would be signaled during the parallel computation of local 3D orientation estimates. As a result, only the misaligned vertex would need to be verified to enable a very rapid response. However, the modified vertex-only 3D contours of Experiment 7 should have given rise to a serious obstacle in the analysis of the vertices. With vertices like those of the quasi-3D contours in Experiment 7, local estimates of 3D orientation are inconsistent across more than one vertex and this inconsistency must be resolved before further analysis of the figure is possible.

In Experiment 7, comparable performances with 3D and quasi-3D vertex-only contours suggest that local estimates of 3D orientation are not necessarily used by participants to extract object structure. The fact that search performance with quasi-3D contours is similar to performance with 3D contours (i.e., similar slopes across both contour types) indicates that grouping of vertices is achieved even though the ensuing structure is not regular. It must therefore be concluded that closure of contour can be computed for a single object (cf. Donnelly et al., 1991) from vertices alone for the purposes of the task, even when the vertices are somewhat misaligned. Such a conclusion is compatible with Donnelly et al.'s finding that the absence of regularity does not preclude preattentive processing. As long as vertices form a closed contour, then the detection of a misaligned vertex might occur in parallel from single-object displays, but multiple-object displays still require serial scanning. Enns and Rensink (1991a, Experiment 5) and Donnelly et al. (1991) reported an increase in search slopes when vertices are not orthogonal compared to search slopes when vertices are orthogonal.

Whether the parallel processes involved in the present task are limited or unlimited in capacity (Townsend & Ashby, 1983) is a question left for future research. The data of the present experiments do not allow a firm conclusion with respect to this issue because processing time for single objects was not assessed as a function of the number of vertices in an object, but future research could address this possibility. For example, Donnelly et al.'s (1991) design could be repeated with vertices depicting 3D objects with varying number of visible surfaces. In addition, limiting the time allowed for processing of objects in a display could delineate the processing capacity of the parallel stage involved in search. This could be accomplished through various experimental techniques, the most obvious being the use of a visual mask (Julesz, 1984; Sagi & Julesz, 1985; Townsend & Ashby, 1983).

CONCLUSION

From the review of pertinent theories and research, it was argued that object-recognition models have not fully resolved how the cognitive visual system arrives at a 3D interpretation from 2D visual images. It was also noted that current models often assume that edges and vertices play a fundamental role in this process. However, as pointed out by Tsotsos (1988), the computational complexity of available line-labeling algorithms make them unlikely accounts of the way in which the visual system deals with the interpretation of line drawings. Thus, models have been proposed, similar to Enns' (1992), suggesting that the visual system examines relatively few local measurements to establish rapidly an estimate of a figure's structure. Vertices are probable locations to obtain such measurements, as suggested by structural-information theorists (e.g., Attneave, 1974) and computer-vision models (e.g., Hinton, 1981). The reported research was designed to examine factors influencing performance in the search for a 3D-orientation difference and for a misaligned vertex when vertex-only contours represent 2D, 3D, and quasi-3D objects, to obtain evidence that some information about object structure can be processed in parallel. Relative differences in performance demonstrate that information obtained from vertices alone is not sufficient to enable an observer to process the structure of multiple 3D objects in parallel. Even though vertices alone may serve to recover the object description of a single object preattentively (Donnelly et al., 1991), such object descriptions are not inherently searched in parallel. Stimulus, display, or task parameters can, however, lead to enhanced search strategies. Two such conditions are repeated practice (demonstrated in four-session experiments) and alignment of objects in a display (demonstrated in Experiment 3). Thus, it is concluded that factors facilitating search enable participants to learn to focus on characteristics of the stimuli and, with practice, become more efficient in their search.

Finally, one issue raised by the comparison of 1- and 2-object displays pertains to the attentional window. Humphreys et al. (cited in Donnelly et al., 1991) suggested that the attentional window is fitted to a single object at a time. This notion is compatible with Kahneman and Treisman's (1984) notion of object-based models. The present data do not contradict this view, but differences between the present data and Donnelly et al.'s (1991) data question whether display parameters, such as the number of objects in a display or the alignment of objects and vertices, are responsible for reported differences. This question is left to future research for an answer.

Feature-integration theory is not seriously compromised by the search functions observed in the present research. Indeed, the theory could benefit from the addition of mechanisms to account for learning (cf. Cave & Wolfe, 1990). Furthermore, the model could be enhanced by suggesting theoretical accounts of relative differences in serial processing times. The model does not currently incorporate empirically-validated accounts of processing changes as a result of practice, even though it alludes to notions of template-matching as a theoretically plausible mechanism (Treisman, 1993; also see Duncan & Humphreys, 1989). Template-matching as a selective mechanism in feature-integration theory, however, has been proposed only as an inhibitory mechanism, filtering out irrelevant information. For Treisman (1993), an inhibitory template is used to reject nontargets: A template is set up to match a randomly selected object in the display and is then used to suppress all matching objects.

Whether a search template is inhibitory (cf. Treisman, 1993) or facilitatory (cf. Duncan & Humphreys, 1989) in nature, the results of Experiments 5 through 7 indicate that a template is not established a priori, otherwise search performance would not change across sessions in the way reflected by the slopes. The characteristic of the present data not addressed by feature-integration theory or other models of visual attention is the change in slopes across sessions. The present data cannot distinguish between an automatization of processes or a modification of a search template. However, these notions are not mutually exclusive and, until data are produced to distinguish between them, both remain viable within an integrated account of visual search.

To the extent that the present experiments have successfully tapped into the early processes involved in the recovery of an object's structure from line drawings, the data suggest that these processes can be modulated by practice, and hence should be considered in light of these findings. To identify a visual feature or characteristic as a preattentive feature should be distinguished from identifying a feature that can, through automatization, be processed in parallel. Similarly, to attribute preattentive processing of a stimulus feature to the feature itself has different implications for object-recognition models than assigning the parallel processing to display features, such as alignment. These distinctions are significant in view of object-recognition models that suggest an initial segregation of a visual scene based on volumetric primitives (e.g., Hummel & Biederman, 1992). According to volumetric models of object recognition, an initial edge-extraction stage provides information for other stages that parse an object at points of concavity (i.e., vertices) and process properties of edges. Brown et al. (1992) examined whether volumetric primitives are detected preattentively. They found that volumetric primitives exhibiting pop out could be predicted by simple 2D features and concluded that volumetric primitives are not processed preattentively. The present research extends the work of Brown et al. and concludes that vertices depicting one such volumetric primitive (i.e., an elongated 3D block) are not inherently processed in parallel in multiple-object displays. By extension, parsing of volumetric primitives, based on information provided by vertices, is not carried out in parallel. The present results must be integrated within models of object recognition, because these models have often assumed a priority of edges and vertices (e.g., Hummel & Biederman, 1992). The present results indicate that the conjunction of lines and line intersection is not processed in parallel in multiple-object displays and should be treated as such in extant models.

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APPENDIX A

Instructions to Participants

A.1

General instructions

Good day,

Please have a seat (POINT TO CHAIR).

Thank you for agreeing to participate in this study.

In this study, we are interested in the speed with which visual information is processed. You will be presented displays of 2-items, 6-items, or 12-items, where each item is a line drawings of a 3D block. In some displays, one of the blocks will be depicted in a different orientation than all the others. Your task will be to determine whether or not such a block is present in the display. I will explain the task in more detail in a short while.

For this study, it is important that we note any difficulties you might have with your vision. Are you aware of any visual problems you may have that would affect your performance in the task?

You will complete two sets of trials. Each set of trials will take 15-20 minutes to complete. In this task, you are asked to indicate whether one of the blocks in the display is in a different orientation than all the other blocks. In fact, you are asked to detect the presence of a specific block in a specific orientation for all trials. The block you are looking for is this block (SHOW HARDCOPY OF BLOCK). Once you have decided whether this block, in this orientation, is present in the display, you will indicate your choice by touching one of these touch-plates. If this block is present in the display, touch the right touch-plate; if it is not, touch the left touch plate.

To use the touch-plates, your palms must be resting on the large plates, with your forefingers on the wooden blocks (the end of the finger flush with the end of the block). Your forearms should be resting comfortably on the table. Give your answer by tapping your index finger once on the small plate and returning your finger to the wooden block after your response.

Each trial will begin with a small fixation symbol in the centre of the screen, followed by a beep. Shortly after that, a display will appear on the screen. Once you have made your decision, touch the right plate if the target block is present in the display, and the left touch-plate if it is not present. **You should try to give your answer as quickly and as accurately**

as possible. About half the time, one block in the display will be different from the others, and about half the time all blocks will be the same.

You will now go through 24 practice trials. Do you have any questions? Please respond as quickly and as accurately as possible. I will address any comments and answer any questions at the end of the practice run.

(After practice) It is important that you give your answers as quickly as possible. It is also important that you try to be as accurate as possible on all trials.

At the end of the first block of trials, you will see a message on the screen indicating your accuracy for this block. Please come and get me at that time. I will then set you up for the remaining trials.

It should take you about 20 minutes to complete all the trials. It's important that you keep the palm of your hands on the large plates at all times. Once again, give your answers as quickly and as accurately as possible.

A.2

Instructions for Experiment 4

Good day,

Please have a seat (POINT TO CHAIR).

Thank you for agreeing to participate in this study.

In this study, we are interested in the speed with which visual information is processed. You will be presented displays of 2-items, 6-items, or 12-items, where each item is a line drawings of a 3D block. The blocks in each display will look something like this (SHOW HARDCOPY OF INCOMPLETE BLOCK). In some displays, one of the blocks will be depicted with a 'flipped' corner. Your task will be to determine whether or not such a block is present in the display; in other words, whether or not a 'flipped' corner is present in the display. I will explain the task in more detail in a short while.

For this study, it is important that we note any difficulties you might have with your vision. Are you aware of any visual problems you may have that would affect your performance in the task?

You will complete two sets of trials. Each block will last between 15 & 20 minutes. In this task, you are asked to indicate whether one of the blocks in the display contains a 'flipped' corner. Each block in the display will look something like that block (POINT TO HARDCOPY OF BLOCK). Once you have decided whether one block in the display contains a 'flipped' corner, you will indicate your choice by touching one of these touchplates. If a 'flipped' corner is present in the display, touch the right touchplate; if not, touch the left touch plate.

To use the touchplates, your palms must be resting on the large plates, with your forefingers on the wooden blocks (the end of the finger flush with the end of the block). Your forearms should be resting comfortably on the table. Give your answer by tapping your index finger once on the small plate and returning your finger to the wooden block after your response.

Each trial will begin with a small fixation symbol in the centre of the screen, followed by a beep. Shortly after that, a display will appear on the screen. Once you have made your decision, touch the right plate if the target is present in the display, and the left touchplate if it is not present. **You should try to give your answer as quickly and as accurately as possible. About half the time, one block in the display will be different from the others, and about half the time all blocks will be the same.**

You will now go through two sets of 24 practice trials. Do you have any questions? Please respond as quickly and as accurately as possible. I will address any comments and answer any questions at the end of the practice run.

(After practice) It is important that you give your answers as quickly as possible. It is also important that you try to be as accurate as possible on all trials.

At the end of the first block of trials, you will see a message on the screen indicating your accuracy for this block. Please come and get me at that time. I will then set you up for the remaining trials.

It's important that you keep the palm of your hands on the large plates at all times. Once again, give your answers as quickly and as accurately as possible.

APPENDIX B

Summaries of Analyses

For each experiment, the slope analysis is reported first. The analysis of mean correct RTs, including polynomial trends are reported next. The analysis of error rates follows. Assumptions of homogeneity of variance were verified and the probability of significance is reported based on the adjusted Greenhouse-Geiser adjusted F-ratio (Geiser & Greenhouse, 1958).

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Experiment 1: Slopes (in ms/item)

Source	df	Mean Square	*F*	*p*
Target Presence (TP)	1	103706.0	69.49	.001
MS_e(TP)	15	1492.4		
Contour Type (CT)	1	3206.0	16.11	.001
MS_e(CT)	15	199.0		
Alignment (A)	1	67767.2	34.42	.001
MS_e(A)	15	1968.6		
TP x CT	1	442.5	2.19	n.s.
MS_e(TP x CT)	15	202.2		
TP x A	1	8163.2	23.14	.001
MS_e(TP x A)	15	352.8		
CT x A	1	24.0	<1.00	n.s.
MS_e(CT x A)	15	72.8		
TP x CT x A	1	11.8	< 1.00	n.s.
MS_e(TP x CT x A)	15	151.6		

Experiment 1: Mean correct RTs (in ms)

Source	df	Mean Square	*F*	*p*
Target Presence (TP)	1	11561300.0	123.93	.001
MS_e(TP)	15	93292.2		
Contour Type (CT)	1	232361.8	24.23	.001
MS_e(CT)	15	9591.6		
Alignment (A)	1	10084800.0	55.26	.001
MS_e(A)	15	182507.8		
Display Size (DS)	2	22400500.0	169.06	.001
MS_e(DS)	30	132503.4		
linear(DS)	1	44651600.0	182.61	.001
MS_e(lin(DS)	15	244522.9		
quadratic(DS)	1	149326.4	7.29	.02
MS_e(quad(DS)	15	20483.8		
TP x CT	1	22662.8	1.75	n.s.
MS_e(TP x CT)	15	12979.7		
TP x A	1	202860.1	7.39	.02
MS_e(TP x A)	15	27454.2		
TP x DS	2	2631863.9	59.95	.001
MS_e(TP x DS)	30	43902.7		
TP x lin(DS)	1	5234658.0	75.20	.001
MS_e(TP x lin(DS))	15	69610.5		
TP x quad(DS)	1	29069.0	1.60	n.s.
MS_e(TP x quad(DS))	15	29069.8		
CT x A	1	4147.5	1.16	n.s.
MS_e(CT x A)	15	3577.6		
CT x DS	2	107699.0	12.61	.001
MS_e(CT x DS)	30	8540.7		

Experiment 1: Mean correct RTs (continued)

Source	df	Mean Square	*F*	*p*
CT x lin(DS)	1	139455.6	15.66	.001
MS_e(CT x lin(DS))	15	8904.5		
CT x quad(DS)	1	75942.4	9.29	n.s.
MS_e(CT x quad(DS))	15	75942.4		
A x DS	2	1790257.6	32.88	.001
MS_e(A x DS)	30	54453.7		
A x lin(DS)	1	3552518.2	35.81	.001
MS_e(A x lin(DS))	15	99205.6		
A x quad(DS)	1	27997.1	2.89	n.s.
MS_e(A x quad(DS))	15	9701.8		
TP x CT x A	1	490.5	< 1.00	n.s.
MS_e(TP Xx CT x A)	15	7677.1		
TP x CT x DS	2	16335.9	2.08	n.s.
MS_e(TP x CT x DS)	30	7870.9		
TP x CT x lin(DS)	1	19095.8	2.09	n.s.
MS_e(TP x CT x lin(DS))	15	9159.6		
TP x CT x quad(DS)	1	13576.1	2.06	n.s.
MS_e(TP x CT x quad(DS))	15	6582.3		
TP x A x DS	2	210388.9	18.26	.001
MS_e(TP x A x DS)	30	11521.5		
TP x A x lin(DS)	1	420633.3	24.28	.001
MS_e(TP x A x lin(DS))	15	17328.0		
TP x A x quad(DS)	1	144.1	<1.00	n.s.
MS_e(TP x A x quad(DS))	15	5715.0		

Experiment 1: Mean correct RTs (continued)

Source	df	Mean Square	*F*	*p*
CT x A x DS	2	3018.1	<1.00	n.s.
MS_e(CT x A x DS)	30	3875.3		
CT x A x lin(DS)	1	1822.2	<1.00	n.s.
MS_e(CT x A x lin(DS))	15	3153.9		
CT x A x quad(DS)	1	4214.1	<1.00	n.s.
MS_e(CT x A x quad(DS))	15	4596.7		
TP x CT x A x DS	2	653.8	<1.00	n.s.
MS_e(TP x CT x A x DS)	30	6612.9		
TP x CT x A x lin(DS)	1	438.4	<1.00	n.s.
MS_e(TP x CT x A x lin(DS))	15	7181.0		
TP x CT x A x quad(DS)	1	869.1	<1.00	n.s.
MS_e(TP x CT x A x quad(DS))	15	6044.7		

Experiment 1: Percentage error

Source	df	Mean Square	*F*	*p*
Target Presence (TP)	1	4717.2	54.26	.001
MS_e(TP)	15	86.9		
Contour Type (CT)	1	23.9	1.08	n.s.
MS_e(CT)	15	22.1		
Alignment (A)	1	4261.3	50.08	.001
MS_e(A)	15	85.1		
Display Size (DS)	2	2233.9	36.62	.001
MS_e(DS)	30	61.0		
TP x CT	1	0.1	<1.00	n.s.
MS_e(TP x CT)	15	13.1		
TP x A	1	1937.4	40.29	.001
MS_e(TP x A)	15	48.1		
TP x DS	2	1645.7	41.21	.001
MS_e(TP x DS)	30	39.9		
CT x A	1	5.5	<1.00	n.s.
MS_e(CT x A)	15	24.1		
CT x DS	2	16.6	<1.00	n.s.
MS_e(CT x DS)	30	6.7		
A x DS	2	879.6	23.72	.001
MS_e(A x DS)	30	37.1		
TP x CT x A	1	3.7	< 1.00	n.s.
MS_e(TP x CT x A)	15	24.4		
TP x CT x DS	2	56.6	2.27	n.s.
MS_e(TP x CT x DS)	30	24.9		

Experiment 1: Percentage error (continued)

Source	df	Mean Square	*F*	*p*
TP x A x DS	2	425.4	18.73	.001
MS_e(TP x A x DS)	30	22.7		
CT x A x DS	2	36.0	1.20	n.s.
MS_e(CT x A x DS)	30	29.9		
TP x CT x A x DS	2	81.9	2.61	.09
MS_e(TP x CT x A x DS)	30	31.3		

Experiment 2: Slopes (in ms/item)

Source	df	Mean Square	*F*	*p*
Target Presence (TP)	1	1209.1	12.96	.003
MS_e(TP)	15	93.3		

Experiment 2: Mean correct RTs (in ms)

Source	df	Mean Square	*F*	*p*
Target Presence (TP)	1	392320.5	31.84	.001
MS_e(TP)	15	12322.0		
Display Size (DS)	2	892380.0	52.00	.001
MS_e(DS)	30	17161.0		
linear(DS)	1	1784562.0	53.41	.001
MS_e(TP x lin(DS))	15	33410.5		
quadratic(DS)	1	198.0	<1.00	n.s.
MS_e(TP x quad(DS))	15	911.5		
TP x DS	2	30707.5	10.32	.001
MS_e(TP x DS)	30	2975.4		
TP x lin(DS)	1	60577.5	12.64	.001
MS_e(TP x lin(DS))	15	4792.2		
TP x quad(DS)	1	837.5	<1.00	n.s.
MS_e(TP x quad(DS))	15	1158.5		

Experiment 2: Percentage error

Source	df	Mean Square	*F*	*p*
Target Presence (TP)	1	461.4	80.46	.001
MS_e(TP)	15	5.7		
Display Size (DS)	2	510.4	55.49	.001
MS_e(DS)	30	9.2		
TP x DS	2	557.4	59.18	.001
MS_e(TP x DS)	30	9.4		

Experiment 3: Slopes (in ms/item)

Source	df	Mean Square	*F*	*p*
Between-subjects factor				
Alignment (A)	1	9532.4	5.91	.03
MS_e(A)	14	1612.1		
Within-subject factors				
Target Presence (TP)	1	12916.3	27.07	.001
A x TP	1	677.1	1.42	n.s.
MS_e(TP)	14	477.2		
Session (S)	3	2870.7	36.52	.001
A x S	3	234.9	2.99	n.s.
MS_e(S)	42	78.6		
linear(S)	1	7907.3	43.10	.001
A x linear(S)	1	622.9	3.40	.09
MS_e(lin(S))	14	183.5		
quadratic(S)	1	679.9	19.48	.001
A x quad(S)	1	81.3	2.33	n.s.
MS_e(quad(S))	14	34.9		
cubic(S)	1	24.9	1.43	n.s.
A x cub(S)	1	0.6	<1.00	n.s.
MS_e(cub(S))	14	17.4		
TP x S	3	174.8	5.19	.03
A x TP x S	3	24.3	<1.00	n.s.
MS_e(TP x S)	42	33.7		
TP x lin(S)	1	493.2	6.23	.03
A x TP x lin(S)	1	27.2	<1.00	n.s.
MS_e(TP x lin(S))	14	79.2		

Experiment 3: Slopes (continued)

Source	df	Mean Square	F	p
TP x quad(S)	1	31.2	1.96	n.s.
A x TP x quad(S)	1	39.8	2.51	n.s.
MS_e(TP x quad(S))	14	15.9		
TP x cub(S)	1	0.1	<1.00	n.s.
A x TP x cub(S)	1	5.8	<1.00	n.s.
MS_e(TP x cub(S))	14	5.9		

Experiment 3: Mean correct RTs (in ms)

Source	df	Mean Square	*F*	*p*
Between-subjects factor				
Alignment (A)	1	1133067.4	6.98	.02
MS_e(A)	14	162324.3		
Within-subject factors				
Target Presence (TP)	1	1151611.6	26.11	.001
A x TP	1	94156.7	2.14	n.s.
MS_e(TP)	14	44110.5		
Session (S)	3	538436.5	45.83	.001
A x S	3	10190.2	<1.00	n.s.
MS_e(S)	42	11747.8		
linear(S)	1	1462192.8	57.36	.001
A x linear(S)	1	24976.9	<1.00	n.s.
MS_e(lin(S))	14	25492.9		
quadratic(S)	1	144887.2	7.60	.001
A x quadratic(S)	1	4475.8	<1.00	n.s.
MS_e(quad(S))	14	8234.5		
cubic(S)	1	8229.5	5.43	.04
A x cubic(S)	1	1117.8	<1.00	n.s.
MS_e(cub(S))	14	1515.9		
Display Size (DS)	2	2609588.6	62.45	.001
A x DS	2	241741.8	5.79	.03
MS_e(DS)	28	41785.5		
linear(DS)	1	5158008.8	64.79	.001
A x lin(DS)	1	479729.4	6.03	.03
MS_e(lin(DS))	14	79608.8		

Experiment 3: Mean correct RTs (continued)

Source	df	Mean Square	*F*	*p*
quadratic(DS)	1	61168.4	15.44	.002
A x quad(DS)	1	3754.2	<1.00	n.s.
MS_e(quad(DS))	14	3961.9		
TP x S	3	42894.3	14.89	.001
A x TP x S	3	3792.2	1.32	n.s.
MS_e(TP x S)	42	2881.6		
TP x lin(S)	1	110458.8	19.14	.001
A x TP x lin(S)	1	6957.8	1.21	n.s.
MS_e(TP x lin(S))	14	5770.3		
TP x quad(S)	1	17617.7	9.20	.009
A x TP x quad(S)	1	1279.7	<1.00	n.s.
MS_e(TP x quad(S))	14	1914.5		
TP x cub(S)	1	606.4	<1.00	n.s.
A x TP x cub(S)	1	3139.1	3.27	.10
MS_e(TP x cub(S))	14	960.1		
TP x DS	2	328051.8		25.88.001
A x TP x DS	2	17433.4	1.38	n.s.
MS_e(TP x DS)	28	12675.7		
TP x lin(DS)	1	637003.5	27.13	.001
A x TP x lin(DS)	1	32806.3	1.40	n.s.
MS_e(TP x lin(DS))	14	23475.9		
TP x quad(DS)	1	19100.1	10.18	.007
A x TP x quad(DS)	1	2060.6	1.10	n.s.
MS_e(TP x quad(DS))	14	1875.5		

Experiment 3: Mean correct RTs (continued)

Source	df	Mean Square	*F*	*p*
S x DS	6	72771.9	31.72	.001
A x S x DS	6	6618.8	2.89	.09
MS_e(S x DS)	84	2294.0		
lin(S x DS)	1	395367.2	44.07	.001
A x lin(S x DS)	1	29337.8	3.27	.10
MS_e(lin(S x DS))	14	8971.2		
quad(S x DS)	1	4932.3	3.63	.08
A x quad(S x DS)	1	3705.2	2.73	n.s.
MS_e(quad(S x DS))	14	1358.1		
cub(S x DS)	1	32715.8	18.35	.001
A x cub(S x DS)	1	3436.9	1.93	n.s.
MS_e(cub(S x DS))	14	1782.9		
TP x S x DS	6	4500.8	4.50	.03
A x TP x S x DS	6	930.1	<1.00	n.s.
MS_e(TP x S x DS)	84	1000.1		
TP x lin(S x DS)	1	25027.8	6.44	.03
A x TP x lin(S x DS)	1	1353.0	<1.00	n.s.
MS_e(TP x lin(S x DS))	14	3883.6		
quad(TP x S x DS)	1	44.2	<1.00	n.s.
A x TP x quad(S x DS)	1	52.3	<1.00	n.s.
MS_e(TP x quad(S x DS))	14	610.0		
TP x cub(S x DS)	1	1670.8	2.03	n.s.
A x TP x cub(S x DS)	1	1570.1	1.91	n.s.
MS_e(TP x cub(S x DS))	14	824.0		

Experiment 3: Percentage error

Source	df	Mean Square	F	p
Between-subjects factor				
Alignment (A)	1	6.5	<1.00	n.s.
MS$_e$(A)	14	63.2		
Within-subject factors				
Target Presence (TP)	1	110.8	4.74	.05
A x TP	1	2.2	<1.00	n.s.
MS$_e$(TP)	14	23.4		
Session (S)	3	7.1	<1.00	n.s.
A x S	3	4.8	<1.00	n.s.
MS$_e$(S)	42	7.2		
Display Size (DS)	2	393.9	22.98	.001
A x DS	2	35.0	2.04	n.s.
MS$_e$(DS)	28	17.1		
TP x S	3	2.1	<1.00	n.s.
A x TP x S	3	2.5	1.00	n.s.
MS$_e$(TP x S)	42	2.5		
TP x DS	2	63.0	5.74	.03
A x TP x DS	2	69.9	6.37	.02
MS$_e$(TP x DS)	28	11.0		
S x DS	6	6.7	1.71	n.s.
A x S x DS	6	4.0	1.02	n.s.
MS$_e$(S x DS)	84	3.9		

Experiment 3: Percentage error (continued)

Source	df	Mean Square	*F*	*p*
TP x S x DS	6	6.0	1.47	n.s.
A x TP x S x DS	6	1.4	<1.00	n.s.
MS_e(TP x S x DS)	84	4.1		

Experiment 4: Slopes (in ms/item)

Source	df	Mean Square	*F*	*p*
Target Presence (TP)	1	76549.1	50.77	.001
MS_e(TP)	7	1507.7		
Session (S)	3	3833.6	9.33	.001
MS_e(S)	21	410.7		
linear(S)	1	11345.5	15.55	.006
MS_e(lin(S))	21	729.8		
quadratic(S)	1	125.4	<1.00	n.s.
MS_e(quad(S))	21	362.1		
cubic(S)	1	29.9	<1.00	n.s.
MS_e(cub(S))	21	140.2		
TP x SS	3	175.4		2.30n.s.
MS_e(TP x S)	21	76.4		
TP x lin(S)	1	414.1	4.10	.09
MS_e(TP x lin(S))	21	101.0		
TP x quad(S)	1	107.6	1.15	n.s.
MS_e(TP x quad(S))	21	93.3		
TP x cub(S)	1	4.5	<1.00	n.s.
MS_e(TP x cub(S))	21	34.9		

Experiment 4: Mean correct RTs (in ms)

Source	df	Mean Square	*F*	*p*
Target Presence (TP)	1	8873910.0	65.58	.001
MS_e(TP)	7	135305.6		
Session (S)	3	842684.9	16.33	.001
MS_e(S)	21	51601.3		
linear(S)	1	2438654.4	24.79	.002
MS_e(lin(S))	7	98372.1		
quadratic(S)	1	81551.3	1.81	n.s.
MS_e(quad(S))	7	45036.5		
cubic(S)	1	7849.0	<1.00	n.s.
MS_e(cub(S))	7	11395.3		
Display Size (DS)	2	17898700.0	54.02	.001
MS_e(DS)	14	331315.6		
linear(DS)	1	35793200.0	56.19	.001
MS_e(lin(DS))	7	637057.1		
quadratic(DS)	1	4193.6	<1.00	n.s.
MS_e(quad(DS))	7	25574.1		
TP x S	3	19448.4	3.98	.06
MS_e(TP x S)	21	4888.6		
TP x lin(S)	1	57149.6	11.90	.02
MS_e(TP x lin(S))	7	4802.1		
TP x quad(S)	1	1145.6	<1.00	n.s.
MS_e(TP x quad(S))	7	7407.9		
TP x cub(S)	1	50.0	<1.00	n.s.
MS_e(TP x cub(S))	7	2455.9		

Experiment 4: Mean correct RTs (continued)

Source	df	Mean Square	*F*	*p*
TP x DS	2	1959771.3	46.92	.001
MS_e(TP x DS)	14	41765.2		
TP x lin(DS)	1	3918950.1	53.86	.001
MS_e(TP x lin(DS))	7	72757.5		
TP x quad(DS)	1	592.5	<1.00	n.s.
MS_e(TP x quad(DS))	7	10772.8		
S x DS	6	98806.8	8.85	.002
MS_e(S x DS)	42	11167.6		
lin(S x DS)	1	582800.0	16.15	.005
MS_e(lin(S x DS))	7	36086.1		
quad(S x DS)	1	50.4	<1.00	n.s.
MS_e(quad(S x DS))	7	2322.8		
cub(S x DS)	1	5899.7	<1.00	n.s.
MS_e(cub(S x DS))	7	17669.4		
TP x S x DS	6	5064.1	2.17	n.s.
MS_e(TP x S x DS)	42	2332.8		
lin(S x DS)	1	21056.6	4.27	.08
MS_e(TP x lin(S x DS))	7	4927.3		
quad(S x DS)	1	19.8	<1.00	n.s.
MS_e(TP x quad(S x DS))	7	1751.3		
cub(S x DS)	1	4382.8	<1.00	n.s.
MS_e(TP x cub(S x DS))	7	4583.7		

Experiment 4: Percentage error

Source	df	Mean Square	*F*	*p*
Target Presence (TP)	1	2439.7	70.78	.001
MS_e(TP)	7	34.5		
Session (S)	3	6.1	<1.00	n.s.
MS_e(S)	21	6.2		
Display Size (DS)	2	1249.6	64.67	.001
MS_e(DS)	14	19.3		
TP x S	3	16.5	4.27	.03
MS_e(TP x S)	21	3.9		
TP x DS	2	1280.5	30.21.001	
MS_e(TP x DS)	14	42.4		
S x DS	6	12.1	2.79.07	
MS_e(S x DS)	42	4.4		
TP S x DS	6	10.0	1.77	n.s.
MS_e(TP x S x DS)	42	5.6		

Experiment 5: Slopes (in ms/item)

Source	df	Mean Square	*F*	*p*
Target Presence (TP)	1	78096.5	64.77	.001
MS$_e$(TP)	7	1209.0		
Vertex Type (VT)	1	58.7	1.80	n.s.
MS$_e$(VT)	7	32.7		
Session (S)	3	10096.5	15.60	.002
MS$_e$(S)	21	647.4		
linear(S)	1	27140.2	18.81	.003
MS$_e$(lin(S))	7	1443.1		
quadratic(S)	1	1025.5	2.75	n.s.
MS$_e$(quad(S))	7	373.4		
cubic(S)	1	2123.9	16.90	.005
MS$_e$(cub(S))	7	125.7		
TP x VT	1	21.7	<1.00	n.s.
MS$_e$(TP x VT)	7	37.2		
TP x S	3	4107.0	9.62	.02
MS$_e$(TP x S)	21	426.9		
TP x lin(S)	1	9899.7	10.24	.02
MS$_e$(TP x lin(S))	7	966.8		
TP x quad(S)	1	847.2	3.84	.10
MS$_e$(TP x quad(S))	7	220.7		
TP x cub(S)	1	1574.1	16.89	.005
MS$_e$(TP x cub(S))	7	93.2		

Experiment 5: Slopes (continued)

Source	df	Mean Square	F	p
VT x S	3	1.5	<1.00	n.s.
MS_e(VT x S)	21	24.9		
VT x lin(S)	1	1.0	<1.00	n.s.
MS_e(VT x lin(S))	7	37.5		
VT x quad(S)	1	2.7	<1.00	n.s.
MS_e(VT x quad(S))	7	19.4		
VT x cub(S)	1	0.9	<1.00	n.s.
MS_e(VT x cub(S))	7	17.9		
TP x VT x S	3	37.5	2.16	n.s.
MS_e(TP x VT x S)	21	17.6		
TP x VT x lin(S)	1	73.9	5.46	.06
MS_e(TP x VT x lin(S))	7	13.5		
TP x VT x quad(S)	1	29.0	1.54	n.s.
MS_e(TP x VT x quad(S))	7	18.8		
TP x VT x cub(S)	1	10.9	<1.00	n.s.
MS_e(TP x VT x cub(S))	7	20.3		

Experiment 5: Mean correct RTs (in ms)

Source	df	Mean Square	F	p
Target Presence (TP)	1	12558700.0	68.69	.001
MS_e(TP)	7	182815.8		
Vertex Type (VT)	1	45937.5	17.99	.004
MS_e(VT)	7	2554.1		
Session (S)	3	2318743.8	27.54	.001
MS_e(S)	21	84207.1		
linear(S)	1	6171454.9	33.52	.001
MS_e(lin(S))	7	184142.5		
quadratic(S)	1	404301.0	9.29	.02
MS_e(quad(S))	7	43535.3		
cubic(S)	1	380475.4	15.25	.006
MS_e(cub(S))	7	24943.5		
Display Size (DS)	2	5048894.1	54.02	.001
MS_e(DS)	14	93465.9		
linear(DS)	1	10085000.0	61.12	.001
MS_e(lin(DS))	7	164996.7		
quadratic(DS)	1	12797.2	<1.00	n.s.
MS_e(quad(DS))	7	21935.2		
TP x VT	1	37367.0	28.80.001	
MS_e(TP x VT)	7	1297.4		
TP x S	3	444023.1	13.11	.006
MS_e(TP x S)	21	33882.0		
TP x lin(S)	1	1072291.6	14.85	.006
MS_e(TP x lin(S))	7	72219.8		

Experiment 5: Mean correct RTs (continued)

Source	df	Mean Square	*F*	*p*
TP x quad(S)	1	106267.0	5.55	.06
MS_e(TP x quad(S))	7	19142.5		
TP x cub(S)	1	153510.5	14.93	.006
MS_e(TP x cub(S))	7	10283.6		
TP x DS	2	2048822.5	58.49	.001
MS_e(TP x DS)	14	35031.9		
TP x lin(DS)	1	4076613.4	67.70	.001
MS_e(TP x lin(DS))	7	60218.7		
TP x quad(DS)	1	21031.7	2.14	n.s.
MS_e(TP x quad(DS))	7	9845.0		
VT x S	3	218.6	<1.00	n.s.
MS_e(VT x S)	21	1591.8		
VT x lin(S)	1	147.4	<1.00	n.s.
MS_e(VT x lin(S))	7	1115.5		
VT x quad(S)	1	263.3	<1.00	n.s.
MS_e(VT x quad(S))	7	1835.1		
VT x cub(S)	1	245.1	<1.00	n.s.
MS_e(VT x cub(S))	7	1824.7		
VT x DS	2	2312.3	1.33	n.s.
MS_e(VT x DS)	14	1742.1		
VT x lin(DS)	1	2407.1	1.67	n.s.
MS_e(VT x lin(DS))	7	1438.3		
VT x quad(DS)	1	2217.5	1.08	n.s.
MS_e(VT x quad(DS))	7	2046.0		

Experiment 5: Mean correct RTs (continued)

Source	df	Mean Square	*F*	*p*
S x DS	6	255988.3	14.64	.001
MS_e(S x DS)	42	17488.7		
lin(S x DS)	1	1365096.6	19.11	.003
MS_e(lin(S x DS))	7	71453.3		
quad(S x DS)	1	11114.6	2.47	n.s.
MS_e(quad(S x DS))	7	4500.5		
cub(S x DS)	1	51104.3	2.81	n.s.
MS_e(cub(S x DS))	7	18158.8		
TP x VT x S	3	988.6	1.02	n.s.
MS_e(TP x VT x S)	21	971.6		
TP x VT x lin(S)	1	1353.4	1.70	n.s.
MS_e(TP x VT x lin(S))	7	794.5		
TP x VT x quad(S)	1	201.3	<1.00	n.s.
MS_e(TP x VT x quad(S))	7	835.4		
TP x VT x cub(S)	1	1411.1	1.10	n.s.
MS_e(TP x VT x cub(S))	7	1284.9		
TP x VT x DS	2	598.3	<1.00	n.s.
MS_e(TP x VT x DS)	14	1473.7		
TP x VT x lin(DS)	1	1160.3	<1.00	n.s.
MS_e(TP x VT x lin(DS))	7	1768.2		
TP x VT x quad(DS)	1	36.3	<1.00	n.s.
MS_e(TP x VT x quad(DS))	7	1179.2		
TP x S x DS	6	105571.7	9.27	.01
MS_e(TP x S x DS)	42	11390.6		

Experiment 5: Mean correct RTs (continued)

Source	df	Mean Square	*F*	*p*
lin(S x DS)	1	509882.2	10.71	.02
MS_e(TP x lin(S x DS))	7	47623.5		
quad(S x DS)	1	72.9	<1.00	n.s.
MS_e(TP x quad(S x DS))	7	2951.6		
cub(S x DS)	1	42204.6	3.79	.10
MS_e(TP x cub(S x DS))	7	11144.9		
VT x S x DS	6	548.1	<1.00	n.s.
MS_e(VT x S x DS)	42	1039.3		
lin(S x DS)	1	4.9	<1.00	n.s.
MS_e(VT x lin(S x DS))	7	1794.2		
quad(S x DS)	1	1468.9	1.76	n.s.
MS_e(VT x quad(S x DS))	7	836.6		
cub(S x DS)	1	93.8	<1.00	n.s.
MS_e(VT x cub(S x DS))	7	913.5		
TP x VT x S x DS	6	1091.1	1.58	n.s.
MS_e(TP x VT x S x DS)	42	690.6		
lin(S x DS)	1	3729.9	5.35	.06
MS_e(TP x VT x lin(S x DS))	7	697.2		
quad(S x DS)	1	101.7	<1.00	n.s.
MS_e(TP x VT x quad(S x DS))	7	375.8		
cub(S x DS)	1	1645.3	1.98	n.s.
MS_e(TP x VT x cub(S x DS))	7	829.3		

Experiment 5: Percentage error

Source	df	Mean Square	*F*	*p*
Target Presence (TP)	1	3033.2	36.48	.001
MS$_e$(TP)	7	83.1		
Vertex Type (VT)	1	537.2	37.02	.001
MS$_e$(VT)	7	14.5		
Session (S)	3	16.4	<1.00	n.s.
MS$_e$(S)	21	22.4		
Display Size (DS)	2	508.2	21.25	.001
MS$_e$(DS)	14	23.9		
TP x VT	1	557.5	39.98	.001
MS$_e$(TP x VT)	7	13.9		
TP x S	3	13.7	<1.00	n.s.
MS$_e$(TP x S)	21	17.2		
TP x DS	2	391.8	15.13	.002
MS$_e$(TP x DS)	14	25.9		
VT x S	3	10.9	2.27	n.s.
MS$_e$(TP x S)	21	4.8		
VT x DS	2	11.6	3.09	.09
MS$_e$(TP x DS)	14	3.8		
S x DS	6	3.8	<1.00	n.s.
MS$_e$(S x DS)	42	7.5		
TP x VT x S	3	15.5	2.29	n.s.
MS$_e$(TP x S)	21	6.8		
TP x VT x DS	2	1.0	<1.00	n.s.
MS$_e$(TP x DS)	14	7.1		
TP x S x DS	6	5.6	<1.00	n.s.
MS$_e$(TP x S x DS)	42	8.9		

Experiment 5: Percentage error (continued)

Source	df	Mean Square	*F*	*p*
VT x S x DS	6	5.7	1.02	n.s.
MS_e(VT x S x DS)	42	5.5		
TP x VT x S x DS	6	3.6	<1.00	n.s.
MS_e(TP x VT x S x DS)	42	5.9		

Experiment 6: Slopes (in ms/item)

Source	df	Mean Square	*F*	*p*
Target Presence (TP)	1	24063.8	33.44	.001
MS_e(TP)	7	719.5		
Session (S)	3	1853.2	18.98	.001
MS_e(S)	21	97.7		
linear(S)	1	5261.8	45.66	.001
MS_e(lin(S))	7	115.2		
quadratic(S)	1	135.1	5.19	.06
MS_e(quad(S))	7	26.0		
cubic(S)	1	162.7	1.07	n.s.
MS_e(cub(S))	7	151.7		
TP x S	3	308.6	4.11	.06
MS_e(TP x S)	21	75.2		
TP x lin(S)	1	913.3	7.60	.03
MS_e(TP x lin(S))	7	102.2		
TP x quad(S)	1	4.4	<1.00	n.s.
MS_e(TP x quad(S))	7	36.1		
TP x cub(S)	1	8.2	<1.00	n.s.
MS_e(TP x cub(S))	7	69.2		

Note. The analysis is based on slopes computed on the basis of mean correct RTs for 2-, 6-, and 12-item trials.

Experiment 6: Mean correct RTs (in ms)

Source	df	Mean Square	*F*	*p*
Target Presence (TP)	1	1816935.5	43.28	.001
MS$_e$(TP)	7	41986.1		
Session (S)	3	413435.8	52.49	.001
MS$_e$(S)	21	7877.1		
linear(S)	1	1097754.1	91.85	.001
MS$_e$(lin(S))	7	11951.4		
quadratic(S)	1	129195.3	35.34	.001
MS$_e$(quad(S))	7	3655.5		
cubic(S)	1	13357.3	1.67	n.s.
MS$_e$(cub(S))	7	8024.3		
Display Size (DS)	3	3283731.3	81.31	.001
MS$_e$(DS)	21	40387.0		
linear(DS)	1	8312278.3	85.26	.001
MS$_e$(lin(DS))	7	97491.8		
quadratic(DS)	1	1538685.2	70.18	.001
MS$_e$(quad(DS))	7	21924.7		
cubic(DS)	1	230.4	<1.00	n.s.
MS$_e$(cub(DS))	7	1744.4		
TP x S	3	36580.4	8.49	.004
MS$_e$(TP x S)	21	4311.0		
TP x lin(S)	1	98297.7	21.41	.002
MS$_e$(TP x lin(S))	7	4590.9		
TP x quad(S)	1	9640.8	6.76	.04
MS$_e$(TP x quad(S))	7	1425.5		
TP x cub(S)	1	1802.6	<1.00	n.s.
MS$_e$(TP x cub(S))	7	6919.7		

Experiment 6: Mean correct RTs (continued)

Source	df	Mean Square	*F*	*p*
TP x DS	3	513186.8	32.23	.001
MS_e(TP x DS)	21	15922.8		
TP x lin(DS)	1	1252063.4	34.93	.001
MS_e(TP x lin(DS))	7	35842.7		
TP x quad(DS)	1	287497.0	27.74	.001
MS_e(TP x quad(DS))	7	10364.4		
cub(TP x DS)	1	0.1	<1.00	n.s.
MS_e(TP x cub(DS))	7	1561.2		
S x DS	9	44326.6	17.60	.001
MS_e(S x DS)	63	2518.2		
lin(S x DS)	1	330955.7	51.36	.001
MS_e(lin(S x DS))	7	6443.9		
quad(S x DS)	1	38951.3	20.77	.003
MS_e(quad(S x DS))	7	1875.0		
cub(S x DS)	1	1071.7	1.90	n.s.
MS_e(cub(S x DS))	7	564.4		
TP x S x DS	9	8404.3	4.38	.04
MS_e(TP x S x DS)	63	1919.5		
TP x lin(S x DS)	1	64713.0	11.35	.02
MS_e(TP x lin(S x DS))	7	5702.7		
TP x quad(S x DS)	1	4310.8	1.69	n.s.
MS_e(TP x quad(S x DS))	7	2557.2		
TP x cub(S x DS)	1	772.1	1.47	n.s.
MS_e(TP x cub(S x DS))	7	526.0		

Experiment 6: Percentage error

Source	df	Mean Square	*F*	*p*
Target Presence (TP)	1	1193.4	61.47	.001
MS_e(TP)	7	19.4		
Session (S)	3	0.8	<1.00	n.s.
MS_e(S)	21	5.2		
Display Size (DS)	3	465.4	28.37	.001
MS_e(DS)	21	16.4		
TP x S	3	6.1	<1.00	n.s.
MS_e(TP x S)	21	7.5		
TP x DS	3	263.1	23.56	.001
MS_e(TP x DS)	21	11.2		
S x DS	9	4.4	<1.00	n.s.
MS_e(S x DS)	63	6.6		
TP x S x DS	9	12.3	2.45	.08
MS_e(TP x S x DS)	63	5.0		

Experiment 7: Slopes (in ms/item)

Source	df	Mean Square	*F*	*p*
Between-subjects factor				
Contour Type (CT)	2	13618.6	4.67	.02
MS$_e$(CT)	21	2917.5		
Within-subject factors				
Target Presence (TP)	1	76288.9	132.26	.001
CT x TP	2	867.5	1.50	n.s.
MS$_e$(TP)	21	576.8		
Session (S)	3	7513.9	35.98	.001
CT x S	6	737.5	3.53	.02
MS$_e$(S)	63	208.8		
linear(S)	1	19251.5	59.87	.001
CT x lin(S)	2	1121.9	3.49	.05
MS$_e$(lin(S))	21	321.6		
quadratic(S)	1	3290.1	13.96	.001
CT x quad(S)	2	913.2	3.88	.04
MS$_e$(quad(S))	21	235.6		
cubic(S)	1	0.13	<1.00	n.s.
CT x cub(S)	2	177.3	2.56	n.s.
MS$_e$(cub(S))	21	69.2		
TP x S	3	615.1	7.39	.001
CT x TP x S	6	188.9	2.27	.08
MS$_e$(TP x S)	63	83.3		
TP x lin(S)	1	1586.7	11.29	.003
CT x TP x lin(S)	2	276.3	1.97	n.s.
MS$_e$(TP x lin(S))	21	140.6		

Experiment 7: Slopes (continued)

Source	df	Mean Square	*F*	*p*
TP x quad(S)	1	248.4	4.48	.05
CT x TP x quad(S)	2	272.9	4.92	.02
MS_e(TP x quad(S))	21	55.5		
TP x cub(S)	1	10.3	<1.00	n.s.
CT x TP x cub(S)	2	17.4	<1.00	n.s.
MS_e(TP x cub(S))	21	53.8		

Note. The analysis is based on slopes computed on the basis of mean correct RTs for 2-, 6-, and 12-item trials.

Experiment 7: Mean correct RTs (in ms)

Source	df	Mean Square	*F*	*p*
Between-subjects factor				
Contour Type (CT)	2	1596194.5	5.93	.009
MS_e(CT)	21	269010.4		
Within-subject factors				
Target Presence (TP)	1	6513790.9	173.13	.001
CT x TP	2	198851.8	5.29.02	
MS_e(TP)	21	37624.1		
Session (S)	3	1949218.5	129.14	.001
CT x S	6	71946.8	4.77.003	
MS_e(S)	63	15094.5		
linear(S)	1	5081369.3	174.64	.001
CT x lin(S)	2	105469.6	3.63	.05
MS_e(lin(S))	21	29095.5		
quadratic(S)	1	754318.7	66.82	.001
CT x quad(S)	2	102163.5	9.05	.001
MS_e(quad(S))	21	11288.2		
cubic(S)	1	11967.4	2.44	n.s.
CT x cub(S)	2	8207.4	1.68	n.s.
MS_e(cub(S))	21	4899.6		
Display Size (DS)	3	14919400.0	216.68	.001
CT x DS	6	371749.9	5.40.01	
MS_e(DS)	63	68855.6		
linear(DS)	1	39929500.0	235.04	.001
CT x lin(DS)	2	1019781.5	6.00	.009
MS_e(lin(DS))	21	169887.8		

Experiment 7: Mean correct RTs (continued)

Source	df	Mean Square	*F*	*p*
quadratic(DS)	1	4713316.7	145.75	.001
CT x quad(DS)	2	61736.9	1.91	n.s.
MS_e(quad(DS))	21	32339.1		
cubic(DS)	1	115490.0	26.61	.001
CT x cub(DS)	2	33731.3	7.77	.003
MS_e(cub(DS))	21	4339.7		
TP x S	3	108380.4	29.73	.001
CT x TP x S	6	7862.7	2.16	.09
MS_e(TP x S)	63	3645.5		
TP x lin(S)	1	267951.5	40.42	.001
CT x TP x lin(S)	2	6181.8	<1.00	n.s.
MS_e(TP x lin(S))	21	6629.0		
TP x quad(S)	1	56701.6	22.03	.001
CT x TP x quad(S)	2	16345.4	6.35	.007
MS_e(TP x quad(S))	21	2574.4		
TP x cub(S)	1	488.1	<1.00	n.s.
CT x TP x cub(S)	2	1060.9	<1.00	n.s.
MS_e(TP x cub(S))	21	1733.1		
TP x DS	3	1713074.2	121.16.001	
CT x TP x DS	6	25482.3	1.80	n.s.
MS_e(TP x DS)	63	14138.9		
TP x lin(DS)	1	4465667.8	131.07	.001
CT x TP x lin(DS)	2	68092.6	1.99	n.s.
MS_e(TP x lin(DS))	21	34071.4		

Experiment 7: Mean correct RTs (continued)

Source	df	Mean Square	*F*	*p*
TP x quad(DS)	1	628090.3	96.25	.001
CT x TP x quad(DS)	2	3384.6	<1.00	n.s.
MS_e(TP x quad(DS))	21	6525.9		
TP x cub(DS)	1	45464.4	24.99	.001
CT x TP x cub(DS)	2	4969.6	2.73	.09
MS_e(TP x cub(DS))	21	1819.3		
S x DS	9	187744.7	35.01	.001
CT x S x DS	18	17020.9	3.17	.01
MS_e(S x DS)	189	5632.9		
lin(S x DS)	1	1342900.4	70.93	.001
CT x lin(S x DS)	2	65421.9	3.46	.05
MS_e(lin(S x DS))	21	18933.3		
quad(S x DS)	1	108003.4	21.01	.001
CT x quad(S x DS)	2	10777.1	2.10	n.s.
MS_e(quad(S x DS))	21	5140.2		
cub(S x DS)	1	4069.2	2.16	n.s.
CT x cub(S x DS)	2	482.2	<1.00	n.s.
MS_e(cub(S x DS))	21	1880.5		
TP x S x DS	9	18037.8	7.86	.001
CT x TP x S x DS	18	4105.6	1.79	n.s.
MS_e(TP x S x DS)	189	2294.1		
lin(S x DS)	1	123378.5	15.41	.001
CT x lin(S x DS)	2	13127.8	1.64	n.s.
MS_e(TP x lin(S x DS	21	8006.5		

Experiment 7: Mean correct RTs (continued)

Source	df	Mean Square	*F*	*p*
quad(S x DS)	1	3578.6	1.91	n.s.
CT x quad(S x DS)	2	4188.6	2.24	n.s.
MS_e(TP x quad(S x DS))	21	1871.9		
cub(S x DS)	1	7441.4	4.81	.04
CT x cub(S x DS)	2	100.5	<1.00	n.s.
MS_e(TP x cub(S x DS))	21	1547.3		

Experiment 7: Percentage error

Source	df	Mean Square	*F*	*p*
Between-subjects factor				
Contour Type (CT)	2	362.7	4.72	.02
MS_e(CT)	21	76.8		
Within-subject factors				
Target Presence (TP)	1	15100.0	222.68	.001
CT x TP	2	399.7	5.89	.009
MS_e(TP)	21	67.8		
Session (S)	3	33.2	1.89	n.s.
CT x S	6	17.8	1.01	n.s.
MS_e(S)	63	17.6		
Display Size (DS)	3	5866.7	176.22	.001
CT x DS	6	67.2	2.02	n.s.
MS_e(DS)	63	33.3		
TP x S	3	8.2	<1.00	n.s.
CT x TP x SS	6	3.8	<1.00	n.s.
MS_e(TP x SS)	63	10.5		
TP x DS	3	4381.9	150.31	.001
CT x TP x DS	6	60.4	2.07	n.s.
MS_e(TP x DS)	63	29.1		
S x DS	9	13.0	1.13	n.s.
CT x S x DS	18	10.5	<1.00	n.s.
MS_e(S x DS)	189	11.5		
TP x S x DS	9	3.7	<1.00	n.s.
CT x TP x S x DS	18	11.3	1.03	n.s.
MS_e(TP x S x DS)	189	10.9		

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Dear Dan:

Re: Permission to reproduce Figures 2 and 7 (pp. 338 and 341) of Enns & Rensink (1991). *Psychological Review, 98,* 335-351.

Permission is hereby granted to reproduce these figures in your dissertation at the University of Alberta.

Sincerely,

Jim Enns, Ph.D.

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20th July, 1994

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Dear Mr. Pilon,

I am happy for you to reproduce Figures 1 through to 4 from the following article.

Donnelly, N., Humphreys, G.W. & Riddoch, M.J. (1991). Parallel computation of primitive shape descriptions. Journal of Experimental Psychology: Human Perception and Performance, 17, 561-570.

Yours sincerely,

G.W. Humphreys, Ph.D.
Professor of Cognitive Psychology.

gwh/ef/djp